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TECHNOLOGY UTILIZATION REPORT

Technology Utilization Division

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(METAL-FORMING TECHNIQUES)

PROPERTY OF:

From

GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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TECHNOLOGY
UTILIZATION REPORT

Technology
Utilization
Division

METAL-FORMING
TECHNIQUES

Prepared for
Technology Utilization Office
GEORGE C. MARSHALL SPACE FLIGHT CENTER

by

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FOREWORD

The Administrator of the National Aeronautics and Space Administration has established a technology utilization program for "the rapid dissemination of information . . . on technological developments . . . which appear to be useful for general industrial application." From a variety of sources, including NASA Research Centers and NASA contractors, space-related technology is collected and screened; and that which has potential industrial use is made generally available. Information from the Nation's space program is thus made available to American industry, including the latest developments in materials, processes, products, techniques, management systems, and analytical and design procedures.

This publication discusses 25 metal-forming techniques currently used in the aircraft and aerospace industries. Some improvements and adaptations developed by the NASA George C. Marshall Space Flight Center and by its contractors are also described.

This report was prepared by Ilia I. Islamoff of Hayes International Corporation in cooperation with F. Bulette of the NASA Technology Utilization Office for the MSFC Manufacturing Engineering Laboratory. The following organizations of the Laboratory contributed to the preparation of this report:

<div align="center">

Manufacturing Research and Technology Division
Experimental Electronics Developments Branch
Methods Development Branch
Metals Processing Section
Mechanical Assembly Concepts Section
Manufacturing Development Division
and Industrial Support Branch

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THE DIRECTOR, TECHNOLOGY UTILIZATION DIVISION, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION.

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INTRODUCTION

The art of metal forming is an ancient one, as evidenced by the Greek and Roman helmets and cuirasses produced by the skill of early-day craftsmen. The wooden mallet, the metal hammer, and the leather sand bag used originally for hand forming of metals are still with us. With the advent of hand-operated machinery, a variety of hand brakes, benders, folders, rollers, crimpers, and rope-type drop hammers appeared and are still in use today.

The development of power-driven machines brought out power hammers, power brakes, a multitude of presses, including hydraulic monsters (50,000 tons), wrappers, stretchers, steam and pneumatic hammers, and the like. All are in use today in combination with tools and dies, some of which are rather sophisticated in nature.

Some of the newer techniques of metal forming have been developed by the Manufacturing Engineering Laboratory of the Marshall Space Flight Center, and others by the aerospace industry companies.

It is the intent in this report to outline the relatively recent metal forming techniques for sheet and plate materials used by the aircraft and aerospace industries and to describe particularly the techniques employed at present. Some of these, such as magnetic forming and hot-drape forming, are in the experimental stage.

It is hoped that the information presented herein will be of some benefit to American industry at large.

GENERAL

The metal-forming techniques developed in recent years and currently used by the aircraft and aerospace industries are as follows:

1. Draw forming
2. Rubber forming
3. Rubber-bag forming
4. Hydroforming
5. Marform
6. Hi-draw
7. Drop hammer forming
8. Impacted rubber forming
9. Hot forming with rubber
10. Androforming
11. Spinforming
12. Die-quench forming
13. Hydrodynamic die-quench forming
14. Metallic shot technique
15. Stretch forming
16. Creep forming
17. Incremental-dish forming
18. Shot peening
19. Hydraulic-bulge forming
20. Age forming and sizing
21. Hot-drape forming
22. Explosive forming
23. Electrohydraulic forming
24. Magnetic forming
25. Roll extrusion (Parform) technique

This report provides a general description of these sheet-metal-forming techniques, augmented by descriptions of recent work accomplished either by the George C. Marshall Space Flight Center (MSFC) or by its contractors.

DRAW FORMING

Conventional draw forming normally utilizes a double-action press, hydraulic or mechanical, and metal male-female matching dies, usually with a blank holder. While this technique is basic in high-production programs such as those associated with the appliance or automobile industries where high tooling costs are justifiable, its use is severely restricted in the aircraft and spacecraft industries where short runs of parts are the rule. Therefore, because of the prohibitive tooling cost for draw forming, the aircraft and spacecraft industries employ other techniques such as rubber forming, drop-hammer forming, or stretch forming, reducing tooling expense to an acceptable level.

RUBBER FORMING

Shaping metals with rubber, generally referred to as the Guerin technique, is perhaps the most widely used hydroforming technique. Normally, a single-action, open-type hydraulic press is used (fig. 1). A 70- to 75-durometer rubber pad, 8 to 9 inches deep, is mounted within a steel pad container attached to the moving ram. This pad takes the place of the conventional female mating die. The male die, which is not necessarily metal but can be made of plastic or masonite, is fastened

to the platen, which fits closely to the opening of the pad holder. As the ram descends, the platen fits into the pad holder, thus confining the pliable, but practically incompressible, rubber. The rubber fills all spaces around the die blocks and transmits pressure in every direction like a fluid, thus forcing the metal blank to take the exact contour of the male die.
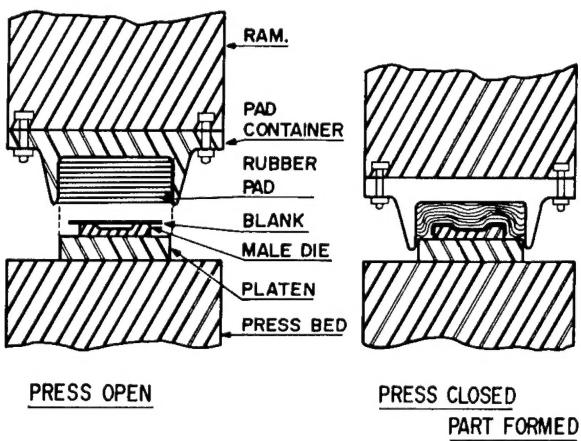
Figure 1.—Forming with rubber on hydropress.

Because mating dies are not needed in this technique, the tooling costs are naturally much lower. Also, the wear and tear on the rubber pad can be minimized by simply laying a separate piece of rubber sheet directly on the blank so that it, rather than the relatively expensive pad, takes the wear. The forming pressures for light gages (0.025 to 0.040 inch) of aluminum alloy are on the order of 1000 to 1100 pounds per square inch, as determined by the rubber pad size versus total press capacity. For heavier gages (0.064 inch) and for stronger aluminum alloys like 7075, pressures on the order of 2000 to 2500 pounds per square inch are required and are obtained either by using a larger capacity press or a smaller pad container. Some hydropresses go to 5000 to 7000 tons capacity. While higher pressures reduce the amount of hand work required on parts after press forming, they introduce stress concentrations in the corners of cast rectangular containers of such magnitude that containers sometimes crack or fail completely. This endangers operating personnel. To eliminate this hazard, containers are fabricated or laminated instead of cast when pressures of 2500 to 3500 pounds per square inch are required. If pressures of 5000 pounds per square inch are required, containers used are round.

RUBBER-BAG FORMING

The rubber-bag forming technique (fig. 2) is a modification of the Guerin technique, designed to utilize direct hydraulic pressure. This is accomplished by using a rubber pad approximately 2 to 2½ inches thick, with the rubber bag or diaphragm located above the pad. Fluid from a high pressure pump is forced into the bag, causing the rubber pad to flow around the contour of the male die.
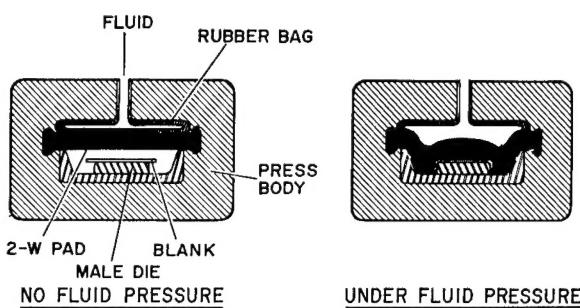
Figure 2.—Rubber-bag forming.

The bag-type press is designed for pressure of substantially higher order than that used in rectangular containers of the straight rubber-forming Guerin technique. Also, the pressure of the bag on the thin rubber pad is uniform. If, for example, the machine is rated at 5000 pounds per square inch, it delivers a true pressure of 5000 pounds per square inch in the pad. Solid rubber does not provide this degree of uniformity or accuracy for the true pressure because a part of the ram pressure is expended in overcoming the internal resistance of the heavy rubber pad employed in a straight Guerin technique.

HYDROFORMING, MARFORM, AND HI-DRAW

The hydroforming, marform, and hi-draw techniques of metal forming can be considered in one group as they incorporate several common principles (figs. 3, 4, and 5).

Operating at high pressures, all three can be classified as draw forming, with male punches working against either a diaphragm or solid rubber, and with movement of the blank restricted as it is held between the rubber and the blank holder. All three techniques feature double-action hydraulic presses.

In hydroforming, a rubber diaphragm closes the
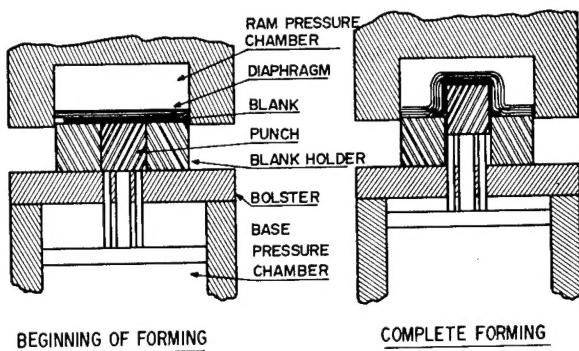
Figure 3.—Hydroforming technique.
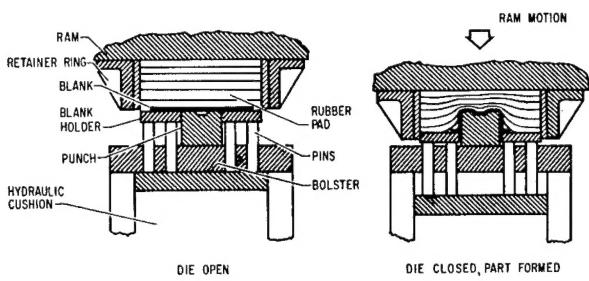
Figure 4.—Marform technique.
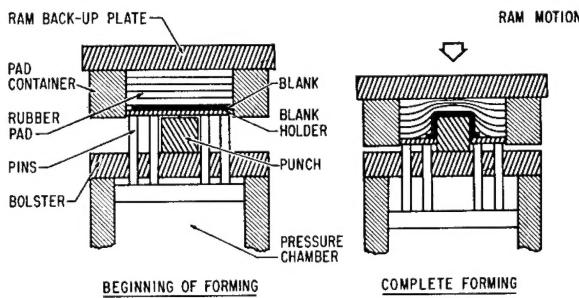
Figure 5.—Hi-draw technique.

ram pressure chamber. The metal is shaped by balancing the pressure of the ram chamber against the pressure of the press base chamber. The punch, mounted on pins and actuated by the pressure of the press base chamber, moves through the blank holder resting on the bolster.

In the Marform and hi-draw techniques, the blank holder is mounted on pins passing through the bolster. The punch is attached directly to the bolster and moves through the blank holder by action of the ram.

Although the size of parts that can be made by these techniques is somewhat restricted because the high pressures used necessitate smaller pad

containers, there are quite obvious economic advantages. In each of these three techniques, as in the straight Guerin technique, the female mating die is, in effect, furnished in any shape required by the male die. Also, more intricate parts in the medium-range gages of aluminum alloy can be formed by employing these methods.

DROP HAMMER FORMING

Generally, two types of drop hammers are used in the aircraft and spacecraft industries: the rope type and the steam or pneumatic type. Both types were adopted from older industries.

The rope-type gravity drop hammer consists of the upper structure, the hammerhead, and the base on a solid foundation. The upper structure is usually supported on the base by four columns. Normally, the male half of the die is attached to the hammerhead and the female half is bolted to the base. The four columns serve as guides for the dropping hammerhead to assure alinement of the dies when they come in contact at the end of the hammerhead drop.

The upper structure of the drop hammer carries a motor-driven rotating shaft with several turns of a 2- to 2½-inch rope coiled around it. One end of the rope is attached to the hammerhead while the loose end is held by the operator so that he can control the hammerhead motion. Manual tension applied to the loose end of the rope tightens the grip of the coiled turns on the rotating shaft, and the hammerhead rises. Releasing tension on the rope turns allows the head with the male die to drop of its own weight. The impact on the blank, resting on the female die, begins shaping the blank to conform to the die. Several drops are usually required to complete the forming of a part.

The pneumatic or steam hammer embodies the same principle of metal forming, that is, the drop of the hammerhead and the male die onto the blank on the female die; however, the up and down motion of the hammerhead is the result of the action of a cylinder and piston combination. The cylinder is a part of the upper structure, while the lower end of the piston rod is connected to the hammerhead.

To raise the hammerhead, compressed air or steam is admitted under the piston by a control valve. Similarly, the compressed air or steam is admitted over the piston to increase impact of the hammerhead drop. The frequency and power of

the impact arc under much better control with the steam or air hammer than they are with the rope hammer, permitting faster action and better quality of work.

The drop-hammer technique is generally used for fairly intricate parts of moderate size but with compound curvatures, sometimes with three- or four-stage dies. Whenever possible, the parts are made with blanks of aluminum alloy in the "as quenched" (AQ) condition after the solution heat-treatment, even though the parts formed in the AQ temper must be worked shortly after quench or the part will harden. The advantage is that forming in the AQ temper minimizes or eliminates completely any distortion, thus usually eliminating the straightening hand work. Examples of the drop hammer parts are shown in figures 6 and 7. Figure 8 shows a Chambersburg pneumatic drop hammer with dies installed.

Figure 8.—Chambersburg pneumatic drop hammer with dies installed.

Figure 6.—Parts made on drop hammer.
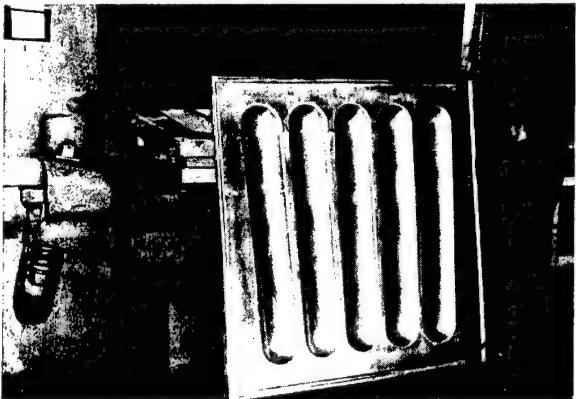
Figure 7.—Part made on drop hammer.

IMPACTED RUBBER FORMING

The impacted-rubber technique is a variant of the principle of metal forming used in the standard hydropress rubber-forming technique. It utilizes a trapped rubber pad in the container attached to the head of a pneumatic drop hammer. The male die is fastened to the platen, which is bolted to the hammer base. The dimensions of the forming area, however, are considerably less than those of a standard hydropress forming rubber pad. This reduction in forming area increases the forming pressure and allows forming of heavier gage material with less hand work. To accommodate higher forming pressures, the rubber pad container and the platen are usually round. The pneumatic hammer, in a few seconds, does the work that would require considerable time with the slow-acting hydropress.

HOT FORMING WITH RUBBER

The fast action of the impacted-rubber forming technique permits shaping of parts while the metal is hot. Generally metals at elevated temperatures are more ductile and can be formed to more severe contours. The elastic recovery is reduced so that spring-back is negligible. The loss of strength exists only while the metal is at elevated temperatures, and full strength is restored when the material has been cooled to room temperature. Aluminum alloys, such as 2219-T62 or T81, can be heated to temperatures as high as 300° to 400° F

and then kept at that temperature for one-half hour to allow for the forming operation. Upon cooling to room temperature, the mechanical properties—the yield, the ultimate strength, and the percent of elongation—are restored almost completely to the original values. Only the yield strength is reduced by approximately 2 to 5 percent if a temperature of 400° F is used. The rubber life is not materially affected by the elevated temperature because of the very short forming-cycle time during which the rubber is exposed to these high temperatures.

ANDROFORMING

The Androforming technique of draw forming without conventional dies is based on the principle of forming by controlled movements and differential elongation in sheet materials (fig. 9 and 10). The contours are established by pulling the sheet material with a set of hydraulically actuated gripper jaws through three stages of the forming elements. The first stage embodies a pair of straight forming elements whose surfaces are on a plane; the second and third stages contain curved forming elements whose contours have been preadjusted. The shape produced is determined by the distance that the first stage is away from, and above or below, the second and third stages, combined with the contours of the second and third stage forming elements.
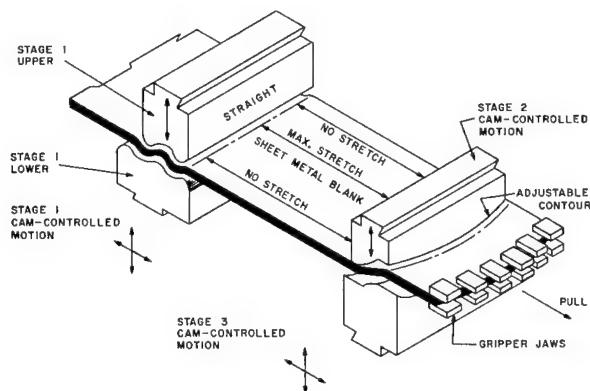
Figure 9.—Movement of material in the Androform technique.

The relationship of the elements is predetermined and programmed into the machine by means of cam-actuated hydraulic tracers. The machine settings are dependent on component configuration, material properties, and sheet thickness and are derived empirically. The nature and configuration of the machine makes it suitable for relatively large parts with shallow contours, such as segments for an antenna or solar reflectors. A male, rib-type checking fixture, corresponding to the required contour, is needed for use in determining machine set-up and preliminary contour evaluation. The machine settings are extremely critical. "Element" contour changes of 0.005 inch and "gap" changes of 0.001 inch produce significant contour variations. Cam changes must be controlled to within 0.005-inch increments to maintain longitudinal-curvature control.

The surface of the blank should be coated with a strippable plastic, or equivalent, to protect the metal finish. The combined thickness of the part and the plastic must be within 0.0015-inch tolerance to assure contour duplication. Best results in Androforming are obtained with material blanks having net-trimmed edges, in which case the contour deviation may be as low as 0.040 inch over most of the part surface.

SPINFORMING

The spinforming technique is not new. Some companies have, for years, specialized in shaping a variety of metals around a rotating mandrel, or male die, some as large as 10 feet in diameter.

Essentially, there are two variants of spinforming. One is the skilled-craft conventional spinning; the other, an outgrowth of the conventional, is known as power-shear spinning. Conventional spinning, in simple form, begins as a circular flat plate, placed in a lathe, between the lathe chuck and the mandrel of a suitable configuration. When the chuck rotates the plate and the mandrel, external pressure is skillfully applied to the plate until it begins to wrap around the mandrel and eventually conforms completely to its contour. Control of dimensional tolerances and metal thinout in conventional spinning is largely dependent upon the operator's skill and it diminishes with an increase in component diameter. Power-shear spinning can be defined as a process which causes a metal blank or preform to take the shape of the rotating mandrel through longitudinal displacement of metal brought about by extrusion under the action of the forming rollers. The MSFC Manufacturing Engineering Laboratory has developed a technique for the power-shear spinning of the 105-inch-diameter Saturn I elliptical bulkheads from 5086 aluminum alloy plate ⅝-inch thick.
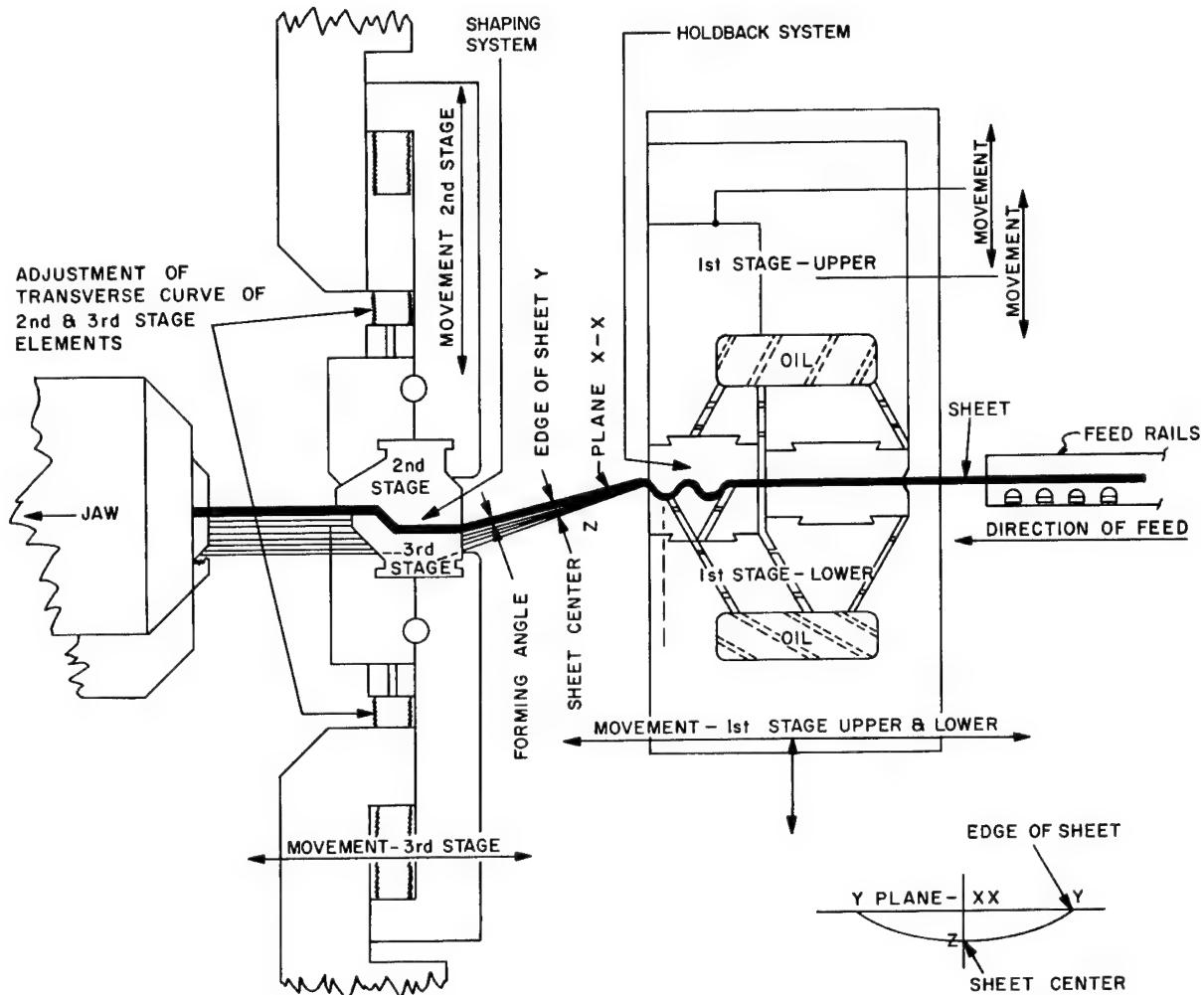
Figure 10.—Movement of forming elements in the Androform technique.
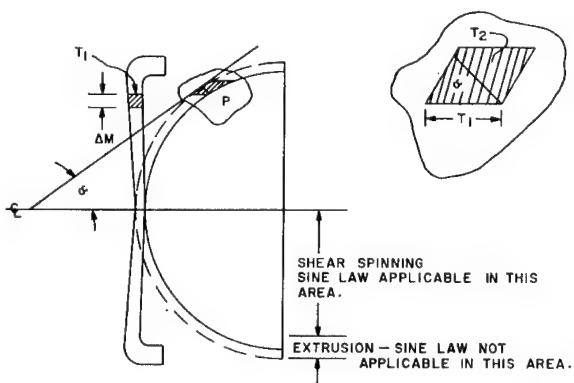
Figure 11.—Application of sine law to power-shear spinning.

T_1 = original blank thickness

T_2 = part thickness at any point (P)

M = increment of metal

$\propto$ = angle formed by intersection of tangent line to P and c

R = % reduction at any point (P)

$$\text{Sine} \propto = \frac{T_2}{T_1} \qquad \therefore T_2 \text{ at any point (P)} = T_1 \text{ Sine} \propto$$

The % reduction (R) at any point (P) is:

$$R = 100(1 - \frac{T_2}{T_1}$$

$$\text{or } R = 100(1 - \frac{T_1 \text{ Sine} \propto}{T_1} \qquad \therefore R = (1 - \text{Sine} \propto)$$

Power-shear spinning is controlled by the so-called "Sine Law." (See derivation on fig. 11.) Metal in the flat disk or preform is displaced longitudinally in increments, parallel to the center of rotation. Since axial thickness remains unchanged, the final wall thickness of the formed part at any point must be equal to the original blank thickness times the sine of the angle formed by the intersection of the axis of revolution and a tangent line to the surface at that point.

Power-shear spinning incorporates the use of precision templates for controlling roller action,

thereby eliminating need for an operator's skill as the determining factor in mantaining dimensional control. Since the finished wall thickness at any point is dependent upon the original blank thickness, it is possible to produce a constant or varying wall thickness by proper design of the blank.

At MSFC, a 10-foot vertical boring mill was modified for the bulkhead spinning by attaching a roller-positioning device to the main structure of the machine. Two-dimensional roller movement
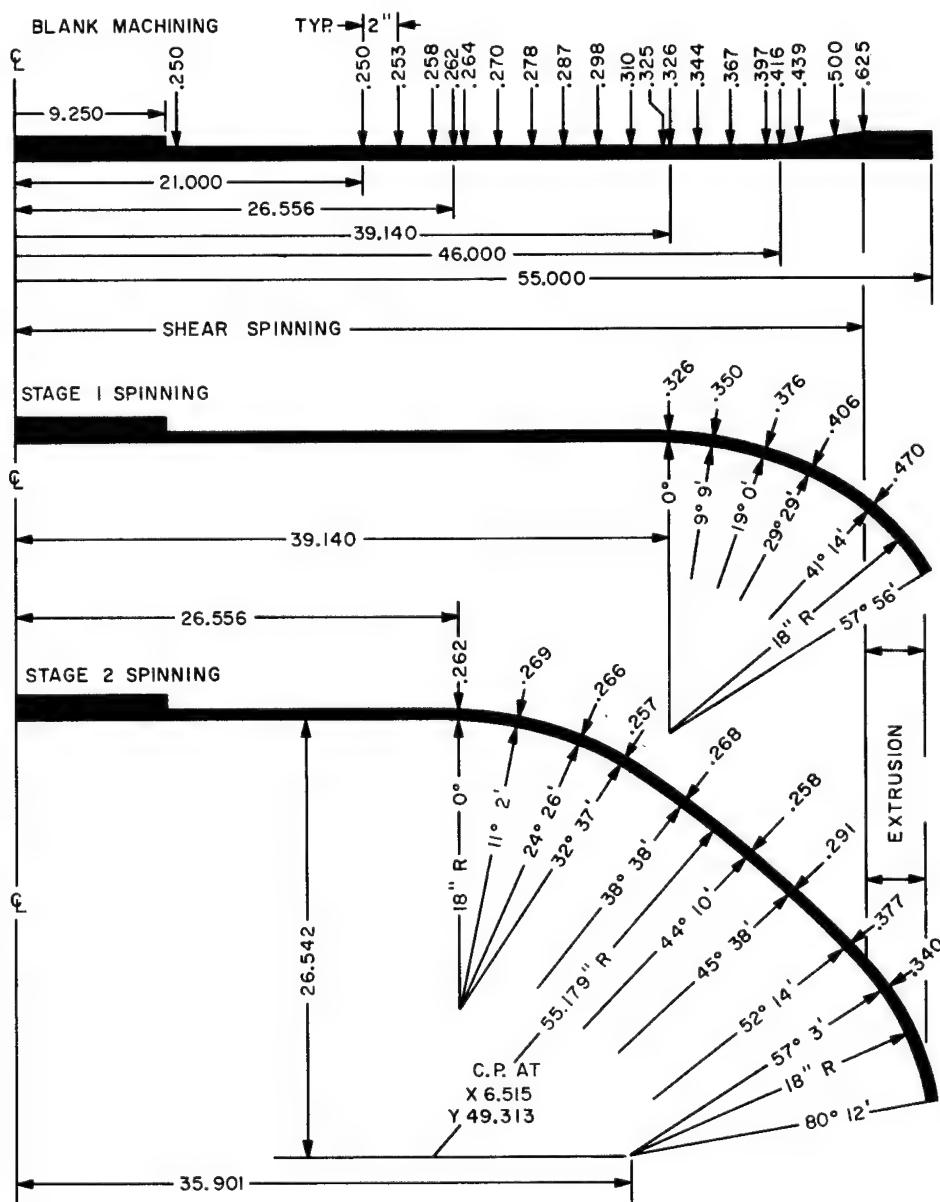
Figure 12.—Blank machining and two stages of spinning.

is effected by the two independently controlled hydraulic cylinders which provide the main and cross-slide movements to the control valve following the template.

Three mandrels, made of cast Meehanite, were required to form the finished bulkhead out of the taper-machined blank. Machining of the blank and the first and second stage preform spinnings are shown in figure 12. The final spun shape is shown in figure 13.

Figure 14.—Actual spinning, 1st stage.

MIN. TENSILE STRENGTH, 38,000 PSI
MIN. YIELD STRENGTH, 30,000 PSI
MIN. ELONGATION, 6%
NOMINAL THICKNESS, 0.225 MIN,
0.255 MAX.

55.179 0.250
SPHER. R

41.362

22°49'

18.00 ±0.250

1.375 REF.

0.230 REF.

0.062 IN.
105-IN. DIA.
0.031 IN.

SECTION A–A

Figure 13.—Final shape of spinning.

Figure 15.—Actual spinning, 2nd stage.

In the preform spinning, the unsupported area of the blank is torch heated to approximately 300° F and spun to the preform configuration. After an annealing treatment, the bulkhead preforms are rerolled to insure more accurate wall thickness. Then the parts are chemically cleaned and fully annealed prior to final spinning. The three stages of spinning are illustrated in figures 14, 15, and 16.

The program for correlating the mechanical properties of cold-worked 5086 aluminum alloy to its hardness was initiated to satisfy the need for a nondestructive technique for inspection of the spun bulkheads. First, material samples were subjected to varying degrees of cold reduction,

Figure 16.—Actual final spinning.

and material hardness, yield strength, tensile strength, and percent of elongation were determined. Then, a graphical correlation between these properties and the percent of cold metal reduction was derived. From this information, the percent of cold metal reduction needed to

satisfy the design requirements for mechanical properties was determined and a graphical relationship of metal hardness to its mechanical properties was made for use as an inspection tool (fig. 17). Although a correlation of this type is not exact, the range of mechanical properties that can be predicted for any given hardness is sufficiently small to allow the use of hardness checks in lieu of destructive testing where the main interest is the assurance of "minimum acceptable mechanical properties."
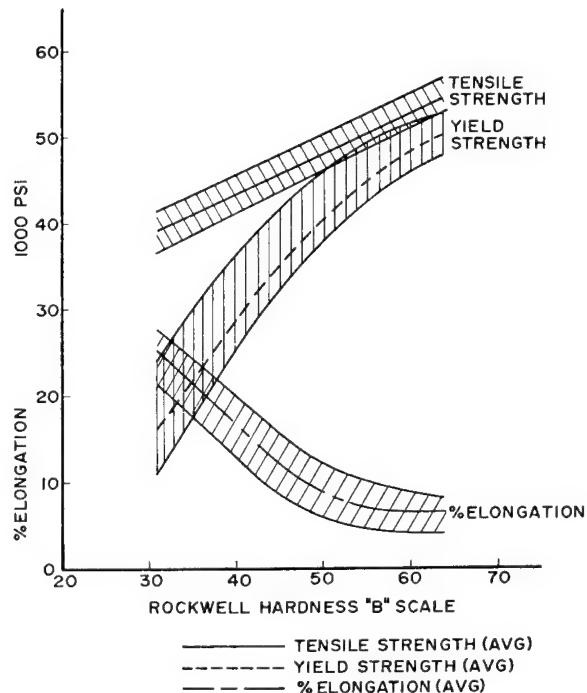
Figure 17.—Hardness and mechanical properties correlation, 5086 aluminum alloy.

For additional vertification, mechanical property tests were made on tensile specimens cut from the first spun bulkhead. The cuts were made parallel and perpendicular to the direction of revolution. The average results obtained from these tests were very close to the design values of the mechanical properties recommended for 5086 aluminum alloy in the H-34 cold-worked condition.

DIE-QUENCH FORMING

The advantage of the die-quench forming technique is that relatively complex parts can be formed free from warpage and residual stresses. Parts of both heavy and light gage aluminum alloys can be successfully formed, limited only by

the size of dies that can be installed in a given press.

In the initial phase of the form-die quench cycle, the blank is placed in a heat-treat furnace and heated to the specified solid-solution temperature. It is held at that temperature until complete and uniform heating of the metal has been achieved. The heated blank is then removed from the furnace and transferred to the lower member of a closely mated forming die anchored to the bed of a press. The upper die member, attached to the press-ram platen, immediately descends and simultaneously forms and cools the blank by metallic conduction through the relatively cold die surfaces. Because the form dies are a large mass of metal, the die surfaces remain cool during a short production run of parts made from relatively thin-gage material. Residual stresses and spring-back are entirely eliminated as the form-die quenching stretches the metal in all directions in fine and uniform increments.

At the heat-treat temperature, the metal expands uniformly in all directions as a natural consequence of the elevated temperature. The permanent deformation of the metal is achieved by subjecting the expanded metal to high forming pressures and maintaining the pressures at equal magnitude throughout the forming operation, thus preventing the metal from contracting while cooling. The percentage of stretch introduced in the metal by form-die quenching is proportional to the coefficient of thermal expansion of the alloy at the processing temperature.

In forming relatively thin gages of material by the die-quench technique, a close-fitting aluminum diaphragm and a ⅛-inch-thick rubber sheet over the lower lead die provide a quenching effect and assure the complete die contact essential in this technique. The upper (female) die is usually made of Kirksite (fig. 18).
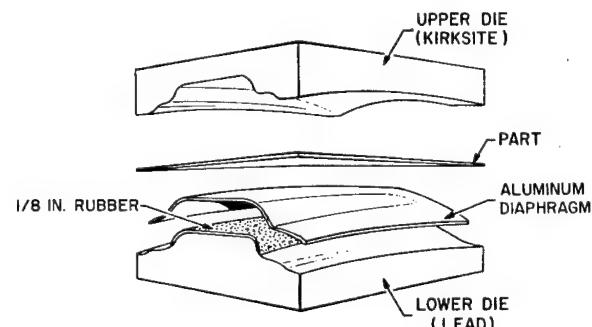
Figure 18.—Die-quench die with aluminum diaphragm.

When heavy sections must be formed by this technique, a large quantity of heat must be dissipated quickly. For this reason, cored-out cavities are provided below the surface of the dies with outlets to the surface. A rubber seal is installed between the two halves of the die, all around the part. Water is circulated through these openings to quench rapidly the die and the part (fig. 19).
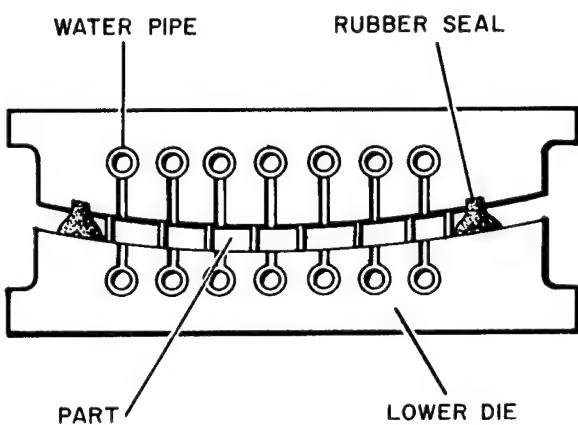
Figure 19.—Die-quench die with water injection.

HYDRODYNAMIC DIE-QUENCH FORMING

Hydrodynamic die-quench forming appears to be particularly suitable for shaping integrally stiffened skins, but its use is limited by the size of the dies that can be installed in a given press. This technique involves the use of high-pressure hydraulic pumps connected by piping to the outlets in the lower (convex) half of the die. As in the straight die-quench forming technique, the part for hydrodynamic forming is heated in the heat-treat furnace to the specified solid-solution temperature and held at that temperature until the part is completely and evenly heated. The heated part is then placed between the dies to be securely held under the ram of the press. Hydraulic pumps introduce the forming fluid into the recessed areas of the part until it conforms to the concave half of the die. The injection of fluid under high pressure not only forms the part but also accelerates the quenching rate to develop higher mechanical properties of the material.

This technique of forming allows some economy in tooling because it eliminates the need for making plugs to support recessed areas of the skin. If the part is formed mechanically, such plugs are

used to prevent the occurrence of flat spots. Also, in machining the part, there is no need for exacting tolerances in the milled cavities because slight variations in skin thickness are automatically compensated for by the fluid. The cross-section of a hydrodynamic die-quench die is shown in figure 20.
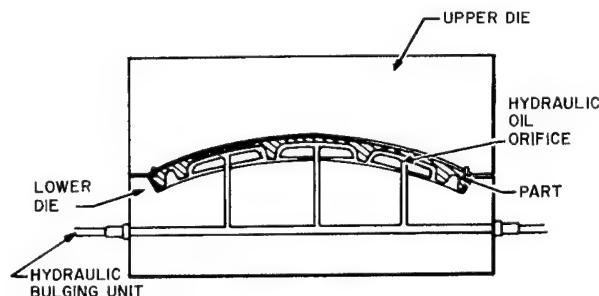
Figure 20.—Die-quench die with high pressure fluid injection.

METALLIC SHOT TECHNIQUE

Metallic shot forming is another variant of the die-quench technique and is used in conjunction with it; that is, the forming cycle follows the die-quench forming procedure.

This technique has been successfully used to form integrally stiffened skins with shallow contours. It affords economy in tooling since only the punch of cast Kirksite is needed as the upper die member to impart the desired curvature to the blank. The lower die member is flexible and consists of a rectangular steel container filled with 0.027-inch steel shot. When the blank, heated to the solid-solution temperature, is placed between the Kirksite punch and the shot, it is quenched by the cool mass of metal as it is being formed under the ram pressure.

In using the form-die quenching technique, attainment of the desired uniform mechanical properties and contour adherence depends, in the main, on the intimate part-to-die contact. When integrally stiffened components and parts with sculptured areas are being worked on, it is quite difficult to obtain satisfactory part-to-die contact because of variations in the cast dies and the part-machining variables.

The advantage of the steel shot is that it affords 100-percent part-to-die contact with relatively low press pressure. The other advantage of this technique is that the flexible die member (steel shot), unlike a rubber pad,

does not have to be frequently replaced. To prevent the shot from getting out and on top of the part, there is a nesting spring-loaded ring all around the shot on the inside edge of the shot container. Figure 21 illustrates the technique, showing dies in open and closed positions. The complexities of modern missile and aircraft parts, the integral stiffening, the heavy sections, and new materials often necessitate forming of parts while the blank is hot.
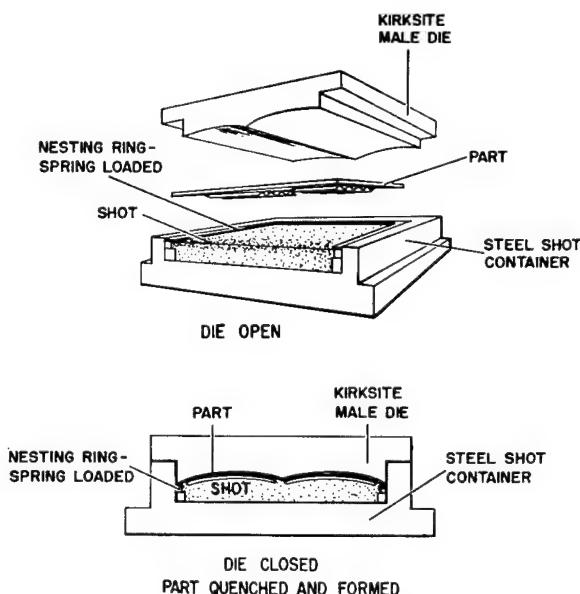
Figure 21.—Metallic shot technique.

The three die-quenching techniques just described can all be classified as variants of the hot-forming technique.

STRETCH FORMING

Stretch forming is a technique of metal forming in which sheet material, firmly held at both ends, is plastically deformed over a male die by the application of stress slightly above the yield strength of the material.

Essentially, there are two types of machines used for stretch forming sheet materials. One type has the stationary gripper jaws mounted on the floor. The male forming die moves up into the work piece which is held in the generally horizontal position by the jaws. Upward movement of the forming die is accomplished by two hydraulically actuated columns, the upper ends of which are joined by a hinged beam structure with the forming die bolted to it. The hinged-structure arrangement permits the die to be tilted in a direction across the work piece when required by the curvature configuration of the die. Usually, the hydraulic system will accommodate either independent or combined operation of the columns. Figure 22 shows horizontal stretching of a bulkhead gore for the Saturn V propellant tank.

The other type of stretch-forming machine has the face of the die and the work piece on a vertical plane. The die is stationary. The jaws, gripping opposite ends of the work piece, are hydraulically actuated and move independently or together, in the horizontal plane in a circular, wrapping motion, bringing the work piece in contact with the die.

Both types of stretch-forming machines often have adjustable segmented jaws that curve automatically to conform to the transverse curvature of the form die. In both types of stretch-forming machines, the variables of the stretch force, the
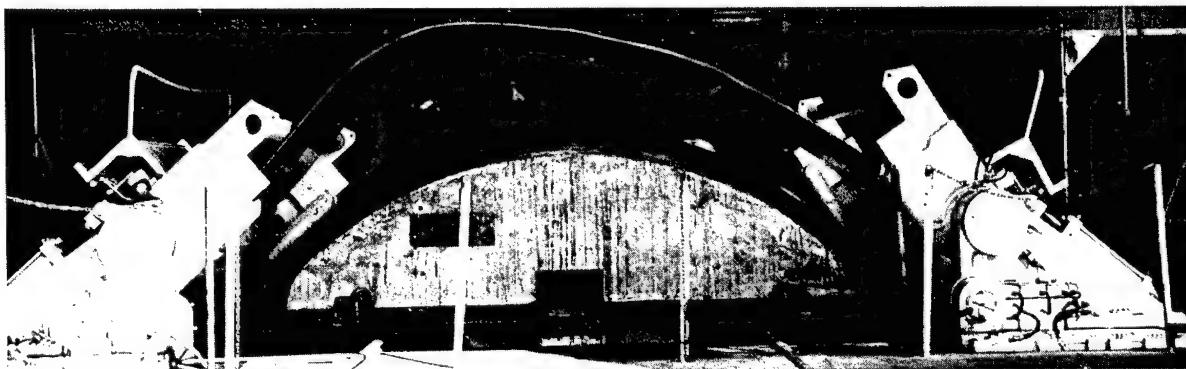
Figure 22.—Stretch-forming tank bulkhead gore.

time or duration of stretching, and the amount of elongation in the material are controlled by the operator to suit the required conditions.

The advantage of the stretch-forming technique, from the tooling standpoint, is that only the male form block is needed without the mating die. Also, for aluminum and other lower strength alloys, a steel form block is not necessary. An adequate block can be made from plastic or from other casting material, such as "Rock Lite," and faced with fiberglass-reinforced laminate. Forming of a hemispherical part on the vertical-type machine is shown in figure 23. Development of the Hufford Hydra-Curve jaws permitted formation of extreme curvatures in sheets with minimum waste in material. This illustration shows how jaw curvatures conform to die shape. The hemispherical part is completely developed in this single operation.

From the fabrication standpoint, the advantage
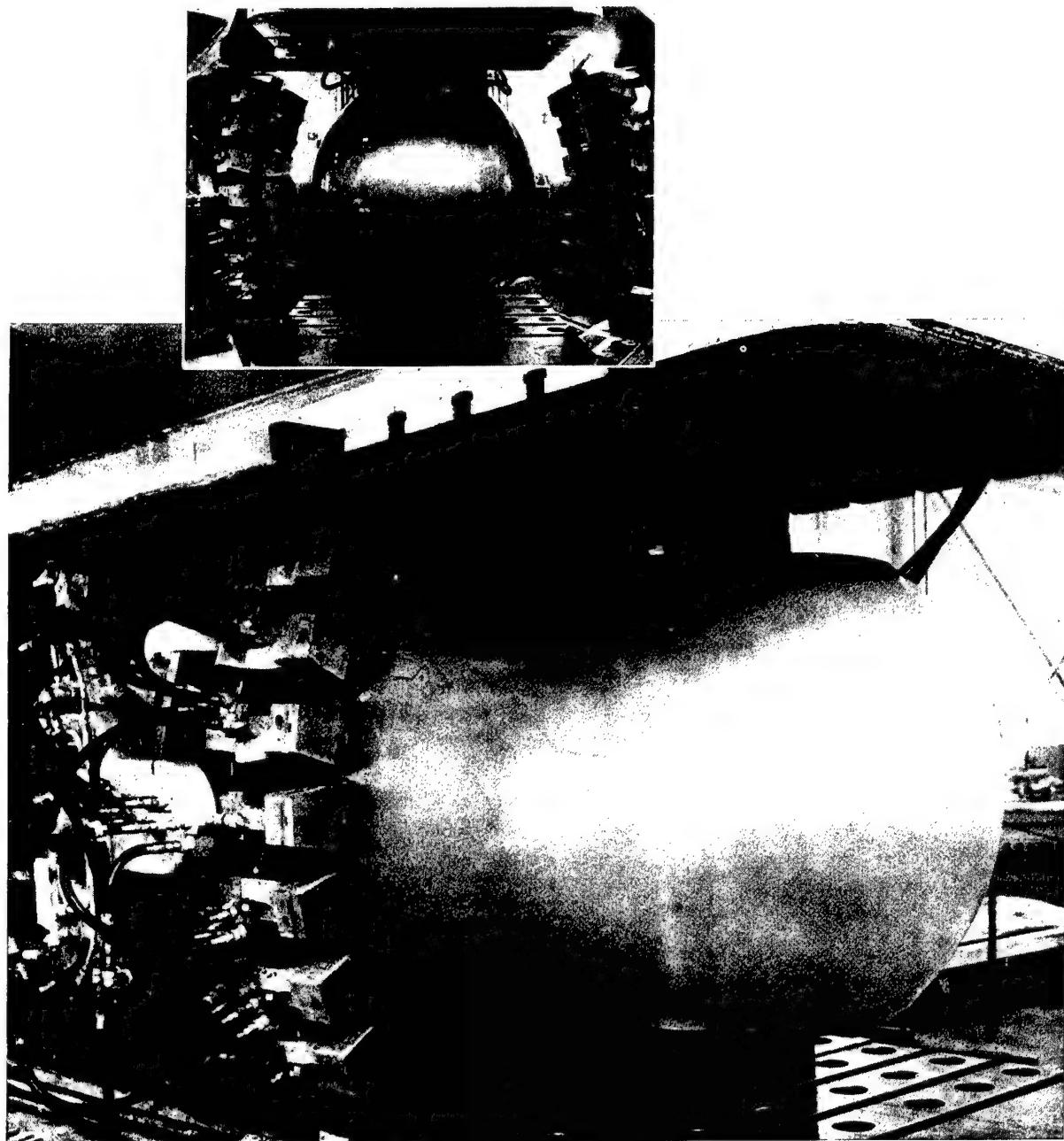
Figure 23.—Stretch-forming hemispherical part in vertical machine.

of stretch forming is that, in many cases, when required contours are not severe, the stretching of aluminum alloy parts can be accomplished in hard tempers, such as 2024-T3, 6061-T4, and 7075-T6, and require no further treatment. In a situation where the form block has rather severe contours, it is preferable to do the stretching in the AQ (as-quenched) condition; however, the stretch marks on the part would be more pronounced. In stretching sculptured parts, it is sometimes necessary to use auxiliary forming devices such as clamps and adjustable straps over the part. This forces the part to remain snug to the die while stretching, and results in closer contour adherence (fig. 24).

A successful method of stretch-wrap forming a sculptured section is shown in the top portion of figure 24. The material is 75S-T6, ⅛-inch thick, sculptured in certain areas to 0.096 inch and 0.072 inch thicknesses. It is heat-treated and start-formed on a 20 foot power roll in the AQ condition. Finish forming in the AQ condition is accomplished on a Hufford Model 46. Note the extra width of material at left end which balances the total cross-sectional area of the sculptured portion with right end.

The clamping device shown is used during the stretch cycle to hold the sculptured section of the skin in contact with the die. This permits the part to pick up friction, eliminating nicking and buckling in the thin areas. The straps hook into the backing plate and contain adjustable screws which exert force against a sheet metal plate. This plate is faced with a ⅛-inch rubber blanket
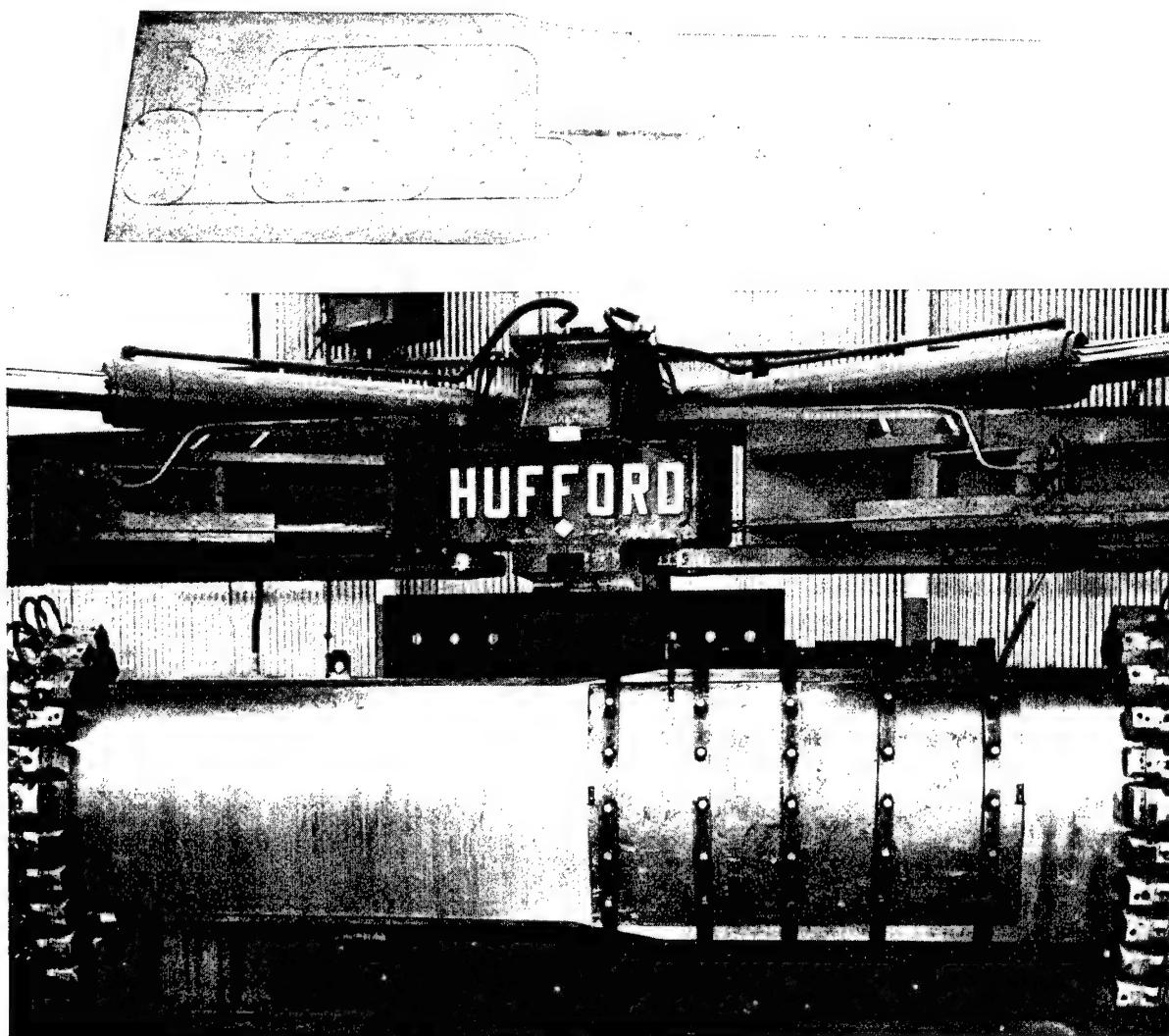
Figure 24.—Stretch-forming in vertical machine with auxiliary straps.

so that the sculptured section can be protected from scratching.

CREEP FORMING

A characteristic of most metallic materials is that of plastic flow or creep deformation. This takes place at stress levels substantially below the normal yield strength when a load is sustained over an extended period of time. Equally well known is the fact that the creep deformation takes place at a faster rate if the temperature of the material is elevated. The creep-forming technique is essentially a stretch-forming process with the addition of heat to the die and consequently to the part. Accordingly, in creep forming, the operator controls not only the three variables of cold-stretch forming, that is, stretch force, stretch duration, and elongation, but also the fourth variable, that of temperature.

One of the main advantages of creep forming is that the technique permits utilization of lower-rated equipment. If the available equipment is not rated high enough to allow stretching of a component at room temperature, the component can be creep-formed hot on the given equipment. The possibility of forming with the reduced power exists because aluminum alloys, such as 2219-T62 or T-81, experience approximately 30-percent drop in the yield and ultimate tensile strengths when heated to 400° F. for one-half hour. When, after forming, the metal cools to room temperature, the mechanical properties are restored almost completely to the original values. With titanium, which is normally formed hot, the temporary reduction in mechanical properties also holds true, except that restoration of the room temperature properties depends on the particular titanium alloy. Some of the alloys require aging or heat treating after forming while others do not.

Another advantage of fabricating by creep forming is that the parts, such as vehicle skins, after forming and cooling, fit the form-die contour exactly, requiring no further hand work or other contouring operations. Experience shows that if a grid is applied to a skin prior to forming, it will exhibit much more uniform elongation over the entire part area than many parts of similar contour which have been stretch-formed at room temperature.

In regard to economy of tooling, as in cold-stretch forming, only one male form die is required because there is no need for a matching female form. Also, no allowance for spring-back or thermal growth in tooling is necessary; the die size is net size. Parts manufactured by this process are as accurate as the tools, exhibiting a very high degree of uniformity. However, because of the need for applying heat to the form die for metallic conduction to the part, the die should be made of hot-rolled steel. In the case of titanium forming, which is usually performed at 1000° F. or more with the die repeatedly subjected to this heat for extended periods of time, it is advisable to use a die made of hot-work tool steel. The dies are generally heated with electric resistance heating units; however, natural gas has been used effectively.

As a more economical alternate to the hot-work tool steel, the stretch-form male die can be made from glassrock or other ceramic materials. The glassrock is a fused, then crushed, silica ceramic. It can be cast to final form at room temperature, and resistance heating wires can be laced through holes near the face of the die that have been cored during casting. This material has an unlimited life cycle up to 1700° F., but it must be handled with care as the impact resistance and flexural strength are low.

Regardless of which die-heating technique is used, thermocouples imbedded in the die surface can control the heat input to the die.

INCREMENTAL-DISH FORMING

The incremental-dish forming technique has been used extensively in the steel fabrication industry to form tank bulkhead shapes similar to those of the Advanced Saturn. However, the dish-forming techniques have not been used on high-strength, heat-treatable aluminum alloys.

The urgent requirement for Saturn V bulkhead gores for tool tryout and subsequent fabrication process development compelled the MSFC Manufacturing Engineering Laboratory to sponsor a contract with a steel fabricating company to develop techniques and to produce aluminum alloy gores by the incremental-dish forming method. The company already had the equipment and standard tooling as well as the knowledge of fabricating similar parts in steel.

Essentially, incremental-dish forming is a technique in which the material is pressed (bumped) between two dies of matched male and female radii by means of a C-frame hydraulic press, which, in this case, was of 200-ton capacity. By

working the material in closely spaced increments of pressings over the entire area, a continuous curved surface is generated.

Two types of standard tooling are used: the "dishing dies" and the "rolling blocks." Both types are 3 feet in diameter. The dishing dies has spherical radii machined into their mating faces, while rolling blocks are double contoured with differing radii in the 90-degree direction on their faces. These are illustrated in figures 25 and 26.

in tempers T42, T37, and T87. The T42 temper material formed readily, but lack of sufficient spring-back resulted in a "bumpy" appearance. The T87 temper proved to have too much spring-back and, although it resulted in acceptable accuracy, forming was too slow to be practical. The T37 temper appeared to be the best, although, to prevent wrinkling of the edges, it was necessary to clamp stiffening angles to both sides of the part around the long dimensions of the edges. The working of the part to obtain compound curvature is shown in figure 27, and the influence of spring-back is shown in figure 28.

Figure 25.—Typical die set.

SPHERICAL RADII

UNIFORM GRID ON PLATE ("BUMPS" ON EACH GRID CORNER)

OVERLAPPING DIE IMPRESSIONS FORM CURVE

MALE DIE

FEMALE DIE, FAR SIDE
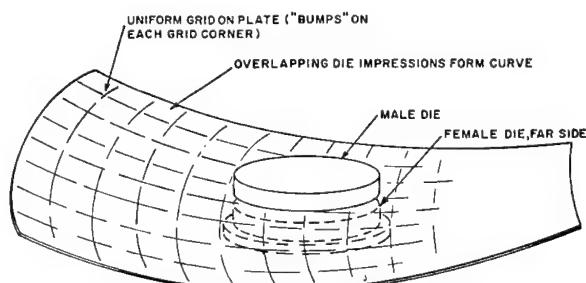
Figure 27.—Spherical dishing.

SECONDARY RADIUS "b"

PRIMARY RADIUS "a"

Figure 26.—Rolling blocks.

AREA OF HIGH STRESS AROUND DIE

UNDER PRESSURE, PLATE CONFORMS TO DIE

PRESSURE RELAXED, METAL SPRINGS BACK NEAR ORIGINAL CURVE
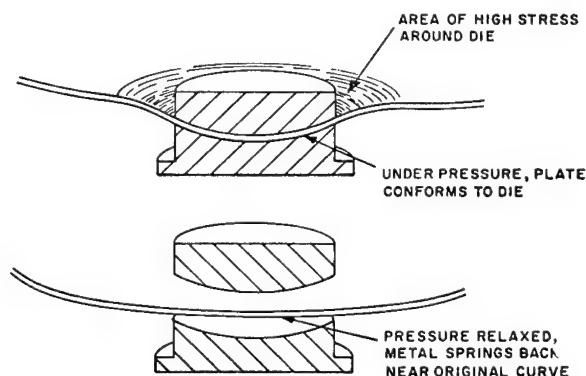
Figure 28.—Influence of spring-back.

The Advanced Saturn bulkhead is 33 feet in diameter and has an elliptical cross-section. Each bulkhead is made up of eight pairs of the apex and the base gores. To evaluate the possibility of dishing and to determine a suitable temper, several sub-scale parts, approximately 4 by 5 feet and ¼-inch thick, were formed in 2219 aluminum alloy

Continuously changing curvature is generated by changing the spacing of the pressings, the wider spacing producing shallower curves. Other changes in curvature are obtained by making the female die shallower with shims, or by changing die facings to different radii. For sharper curvature changes, rolling blocks must be used.

In this manner, several full-scale base and apex gores of 2219-T37 aluminum alloy were formed for the Advanced Saturn. The sequence and elements of the operation are illustrated in figure 29.

An apex gore with edge-restraining angles is shown in figure 30. Standard tooling, covered with rugs to protect the aluminum finish, was used.

Die changeovers had to be made several times, especially during final stages of shaping to the fixture, and it became evident that improvement in tool changeover time was highly desirable. Drastic reduction in machine down-time was achieved with the introduction of a set of fiberglass facings which fit the faces of a standard die block. These facings consisted of a pair of completely contoured matched tools, designed and manufactured for this particular purpose. When the experimental pair proved to be successful, a complete line of fiberglass tools was built for the forming process. Since the base dies do not change, re-

ROUGH TRIM BY PLASMA ARC

DISH-FORM ALL EDGES TO DEVELOPED INTERIM CURVATURE

ATTACH ANGLE IRON RESTRAINING MEMBERS TO BLANK EDGES AND DISH-FORM CENTER

REMOVE EDGE-RESTRAINING MEMBERS AND DISH EDGES OF BLANK. REPEAT STEPS 3 AND 4 AS REQUIRED

REATTACH EDGE-RESTRAINING MEMBERS AND ROLL FOR FINAL SHAPE

REMOVE EDGE-RESTRAINING MEMBERS

FINAL FIT TO JIG BY ROLLING, DISHING, TRIAL, AND CORRECTION

Figure 29.—Elements of incremental-dish forming.
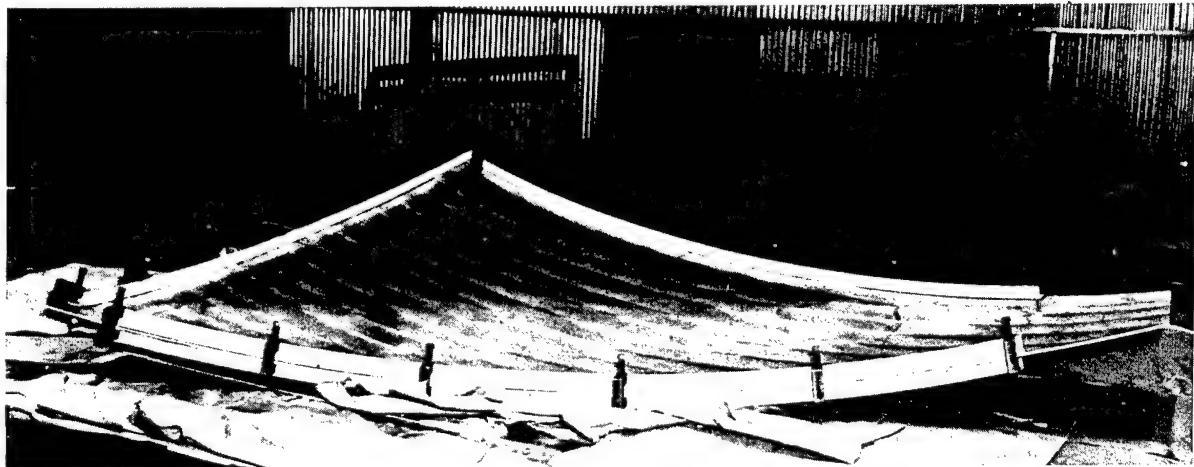
Figure 30.—Edge-restraining angles in place on gore.
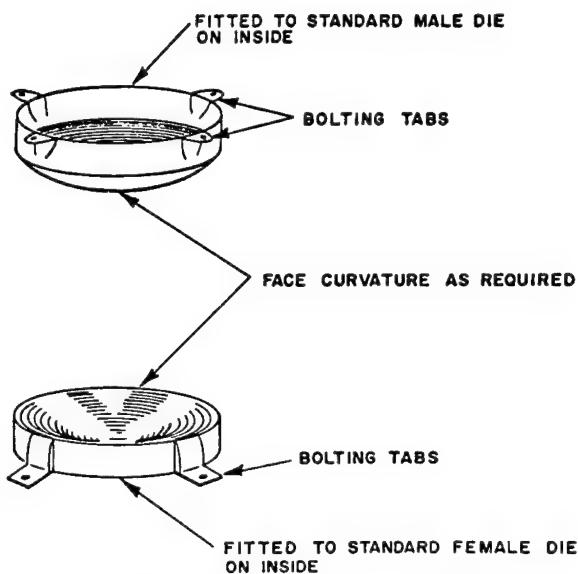
Figure 31.—Fiberglass shell covers for standard pads.

placement of the lightweight fiberglass facing requires only a few minutes. The quick-change feature of these tools made the operator much less reluctant to use different facings when such change would benefit forming. In addition, the relatively soft fiberglass gave the aluminum sufficient protection to make the rugs unnecessary. The fiberglass shells or facings for standard dies are shown in figure 31.

With the completion of the required number of full-scale apex and base gores, it can be said that the incremental-dish forming technique lends itself readily to a prototype and short-run fabrication. Tooling cost is low and the lead time is very short.

The approximately 10- by 14-foot gores were repetitively formed within normal limits of contour accuracy of ±0.250 inch. This is reduced to less than 1/16-inch deviation from true contour after the part is aged under restraint. An apex gore on the check fixture is shown in figure
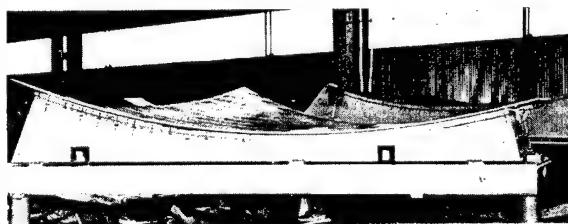
Figure 32.—Apex gore in check fixture.

32. The component accuracy of fit to the fixture is largely dependent on the operator's skill and is directly related to the number of press hours expended in refinement.

Parts formed by this technique are likely to have a greater degree of distortion when subsequently processed through metal removing operations than the parts formed by uniform stressing techniques. This is attributable to the uneven distribution of the residual-forming stress. The degree of deviation will range from negligible, for parts aged after forming, to several inches for parts formed in fully heat-treated and aged temper. The technique, however, is capable of reshaping sculptured components.

SHOT PEENING

Shot peening has been used for years as a means of improving fatigue-life characteristics of highly stressed metal parts. In the last several years, it has been adapted to impart curvature, plain or compound, to such parts as integrally stiffened skins. Shot peening is a mechanical cold-working technique involving bombardment of the metal with thousands of steel pellets or round shot under controlled conditions by means of air pressure. The impact of the shot causes the outside metal surface to spread, thus setting up compressive forces on the opposite side. The unbalanced forces within the part cause it to curve in the direction of peening.

The peening is done while the part is restrained on a fixture of appropriate curvature, the radius of which is developed empirically. The part on the fixture is attached to a table which is tilted to allow the shot to fall away from the work area as a travelling carriage, housing the nozzles, passes over the part. To control the amount of curvature of the part, the operator can vary the air pressure propelling the shot, the area of pressure application, the rate of carriage travel or dwell time, nozzle clearance, and nozzle oscillation. Greater peening intensity or air pressure is required on thick sections.

On successive runs, the operator learns to control all the variables in order to form acceptable parts; however, reproducibility is difficult and dimensional deviations are inconsistent. Another cause of nonuniform results is nozzle clogging. Some skin panels require brake-press forming on the ends to correct flatness.
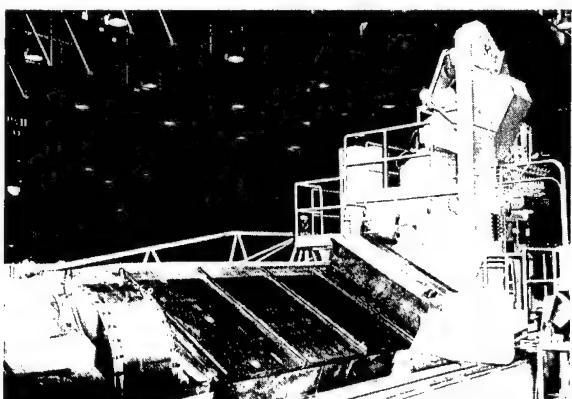
Figure 33.—Integrally stiffened panel on restraining fixture in shot-peen machine.

The technique has the advantage, however, of imparting compressive forces on both surfaces of a part, which tends to improve the fatigue resistance by eliminating areas of tensile-stress concentration. This protects the surface against stress corrosion. Figure 33 shows a sample of integrally stiffened skin panel on the restraining fixture mounted in the shot-peen machine.

HYDRAULIC-BULGE FORMING

Generally, hydraulic-bulge forming is used for parts having a relatively shallow compound curvature. It is a technique in which sheet or plate material is bulged into the concave half of a die by applying hydraulic pressure directly to the surface of the part being formed. Both halves of the die have corrugated or serrated edges which firmly grip the material. The dies also have a fluid seal in the form of an O-ring, or equivalent.

When hydraulic pressure is applied on the side of the material blank opposite the cavity, the blank is forced to stretch. As the fluid is pumped, the stretching continues until the blank rests firmly against the entire area of the die cavity. When movement of the blank has ceased, the pressure is increased sufficiently to assure complete conformity to the die cavity. If the part to be formed is not very large, the two halves of the die can be held securely together, while under hydraulic pressure, by a press of suitable size. However, when dimensions of the part go beyond the size of the available presses, the two halves of the die can be clamped together by the required number of individual hydraulic cylinders, set side by side. This saves the cost of a huge hydraulic press and reduces the required lead time. The concave

portion of a die can be either the upper or the lower half, depending on circumstances and the part configuration.

While the hydraulic-bulge forming technique is not new, the application of this principle to the forming of aluminum alloy blanks on the order of 200 square feet in area is quite recent. The 33-foot-diameter oxidizer and fuel tank bulkheads of the Advanced Saturn V, S-1C Stage, each require 16 pairs of apex and base gores, plus a 54-inch-diameter center piece. They are all hydraulic-bulge formed.

At MSFC, the die for bulging the 54-inch-diameter center piece was designed, procured, and installed in a 1200-ton hydraulic press. The lower half of the die, containing the concave plastic insert of the required contour, was attached to the bed of the press. The upper half of the die, complete with fittings, hoses for pumping the fluid in and out, and vent line with the valve, was bolted to the ram of the press. Mating corrugations for gripping the blank were machined on the edges of both halves of the die. Installation of the die halves in the press is shown in figure 34.
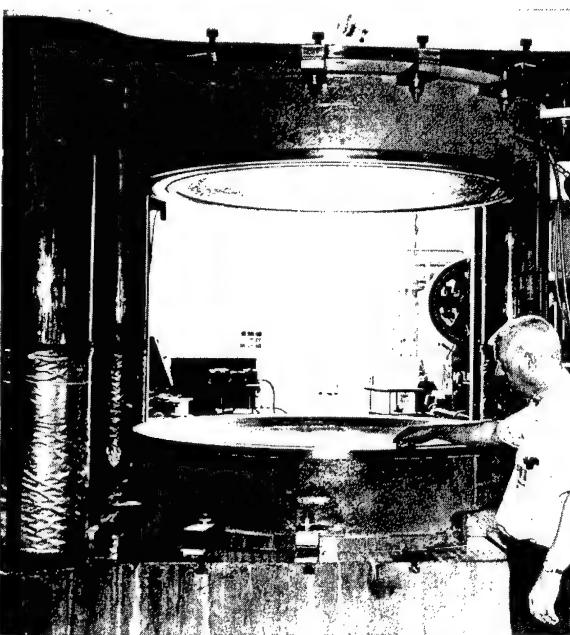
Figure 34.—Top and bottom die halves of hydraulic-bulge tooling for 54-inch center piece.

A total of 12 circular 68-inch-diameter blanks were prepared from 2219-T87 age-tempered aluminum alloy. Six blanks were 0.250 inch thick and six were 0.312 inch thick. The 12

blanks were bulged in 23 pressure-application cycles; some blanks were worked only once, others two or three times, with varying degrees of success. Three blanks were free-formed without the removable plastic insert and were monitored by a dial indicator. The balance were formed with the insert machined to different spherical radii and depth.

Normally anticipated difficulties were encoun-

tered in the empirical development of the particular radius for the insert that would form a blank to the required contour. Subsequent operations of circle-trimming excess material, cutting the center hole, and chemical milling all affected the contour of the hydraulic-bulge formed parts. The results of the development work are given in table I.

Table I. — Bulge forming of 54-inch center pieces

All material is aluminum alloy 2219-T87
Yield Strength: 55,380-58,020 psi

Ultimate Strength: 67,650-70,450 psi
Elongation: 8-11 percent

| | Blank | | Spherical radius of insert inches | Depth of insert inches | Permanent set inches | Change in blank diameter inches | | | Comments |
No.	Thick-ness inches	Cycle				Spring-back inches	During forming	Perma-nent	
1	0.2550	A and B	277-27/32	1.310	Negligible	1.310	. . .	. . .	No forming.
		C	Free-formed (sharp edge on 56½-inch die cavity).	2⅝	7/32	2.4	. . .	. . .	Too shallow.
		D	Fee-formed with sharp edge.	3.3	. . .	. . .	. . .	. . .	Too shallow.
		E	100 R.	3⅝	2	1⅝	. . .	. . .	⅝ in. too deep.
2	.250	A	Free formed.	3.90	See comments	. . .	. . .	. . .	⅜ in. overformed in direction of rolling; 1/16 in. overformed in transverse direction; after trimming, ¼ in. overformed in longitudinal direction; 1/10 in. overformed in transverse direction.
3	.250	A	Free-formed with radiused edge.	. . . .	. . .	. . .	. . .	. . .	. . . .
		B	126 R	2-15/16	15/16	2.00	0.240	. . .	¼ in. to ⅜ in. too shallow.
4	.250	A	126 R	2.94	0.94	2.00	.240	. . .	⅜ in. too shallow.
		B	126 R	2.94	. . .	. . .	. . .	. . .	Blank had ¼-in. shim underneath; effort was not successful because system leaked.
		C	120 R	3.15	1.16	2.00	.240	0.040	5/32 in. too flat.
		D	113 R	3.450	1-7/16	2.00	.240	.230	⅛ in. too deep when formed; ⅛ in. too flat when trimmed.

Table I. — Concluded

No.	Blank Thickness inches	Cycle	Spherical radius of insert inches	Depth of insert inches	Permanent set inches	Spring-back inches	Change in blank diameter inches During forming	Permanent	Comments
5	.312	A	126 R	2.94	0.88	2-1/16	. . .	. . .	7/16 in. too flat.
		B	120 R	3.15	¼ -inch. too flat	. . .	. . .	. . .	¼ in. too flat when formed; ¾ in. too flat when trimmed.
6	.312		113	3.450	1.45	2.00	.300	.260	⅛ in. too deep when formed; 7/32 in. too flat when trimmed; slight change in contour when 8½ in. center hole was cut.
7	.250		113	3.450	1.45	2.00	.300	.260	⅛ in. too deep when formed.
8	.312		102	3.75	1.70	2.05	.300	.300	⅜ in. too deep when formed; 3/16 in. too deep when trimmed.
9	.250		102	3.75	. . .	. . .	.380	.340	⅜ in. too deep when formed; 3/16 in. too deep when trimmed.
10	.312		102	3.75	. . .	. . .	. . .	. . .	A 36-in. diameter ¼-in. pad was placed in center of insert; 1/16 in. under-formed; 11/32 in. too shallow after trimming.
11	.312	A	102	3.75	1.70	2.05	.360	.310	⅜ in. overformed.
		B	102	3.75	1.70	2.05	. . .	.200	A 36-in. diameter ¼-in. rubber pad was placed in center of insert; ⅜ in. over-formed; 1/16 in. to 3/32 in. over-formed after trimming.
12	.312	A	102	3.75	. . .	. . .	.200	. . .	Diameter of blank was permitted to pull in 0.200 only; negligible forming.
		B	102	3.75	1.20	2.55	. . .	. . .	⅛ in. underformed; 7/16 in. under-formed after trim-ming.

The plastic insert has been remachined five times during the development, starting with a final required contour, 277-27/32 inches in radius and 1.31 inches in depth, and finishing with 102 inches in radius and 3.75 inches in depth.

Of the 12 formed parts, the most satisfactory was no. 11, which, after the second cycle of forming with a ¼-inch rubber insert, was only 1/16-3/32 inch overformed after trimming. The free-formed blank exhibited a tendency to form unsymmetrically as explained in table I for blank no. 2.

Two of the parts had approximately 0.150 inch removed by chemical milling from the convex side. The two reacted unequally; one part only deepened 0.10 to 0.30 inch while the other deepened in the rolling direction and flattened irregularly in the transverse direction. This was probably a result of the unequal release of residual stresses by the chem-milling process.

The cutting of an 8½-inch-diameter hole in the center of one blank flattened it 1/16 inch in the rolling direction and deepened it 1/16 inch in the transverse direction.

Four blanks were initially scribed with a 2-inch grid for elongation measurements after forming. The resultant stretching of the material was insignificant, being on the order of 1/64 inch in a 56-inch diameter. This indicates that the diametral flow-in of the material has always occurred and is a major cause of variations in springback since the material is not plastically deformed but is subject to the differences in mechanical properties of the blanks. This stretching occurred in spite of the fact that it was necessary to maintain the full ram pressure of the 1200-ton press at all times while forming to avoid hydraulic fluid leakage. Only 180 to 200 pounds per square inch was required for the forming operation. Increase in the fluid pressure to 500 pounds per square inch was not effective in setting the material to the die contour.

The project, although not fully completed, has proven the hydraulic-bulge-forming principle and has shown the limitations of the process and of the die as designed. The development work could not be continued as the die was scheduled for shipment to the prime contractor for production use.

In regard to the work being done by the prime contractor on hydro-bulging the gores, it is to be noted that they vary in thickness from 0.195 inch to 0.830 inch for apex gores and from 0.224 inch to 0.730 inch for base gores. Some gores are presculptured by machine before forming, others are chem-milled after forming, and still others are of constant thickness. However, as the first step, all gores are machined to the initial required thickness.

Since gore panels with varying thicknesses will naturally have different amounts of stretch, the blanks were developed empirically. All gore material for bulge forming is 2219-T37 aluminum alloy for subsequent heat treatment to T87 condition, either at MSFC or by the prime contractor. Gores that will later have fittings welded into them at MSFC are supplied in T37 temper and, after welding, are aged to T87 temper in a restraining heat-treat fixture. This provides contour correction up to 90 percent. Prior to bulge forming, the gore panels are rolled to a radius of approximately 195 inches.

Because of the large size of the gore blanks (115.0 inches by 230.0 inches for the base gore and 144 inches by 210 inches for the apex gore), two special, fabricated steel, hydraulic-bulging machines had to be designed and built for the job. (See fig. 35.) Each of the two lower die frames contains a pocket for the cured neoprene bag which holds the forming fluid. The bags, however, developed leaks under high pressure and were replaced by the V-shaped, pressure-energized seals to allow the fluid pressure to be exerted directly on the work piece.

Each of the two upper die frames has a cavity for forming the finished shape of each gore. The contours of the cavities were developed to allow for 1-inch overform to compensate for the springback which normally occurs in this type of forming. The hydraulic clamping cylinders (38 for the base and 34 for the apex gores) are mounted around the four sides of the lower frames on each die.

Hydraulic controls for each machine are interlocked so that: (1) pressures greater than the design limit of 1500 pounds per square inch cannot be applied for forming, (2) fluid pressure cannot be built up in the forming cavity until full pressure is applied to the clamping cylinders, and (3) clamping pressure in the cylinders cannot be released until the forming pressure is released.

A forming-process technique for each gore pattern has been developed by trial and error, based on the thickness of the blank and the size and
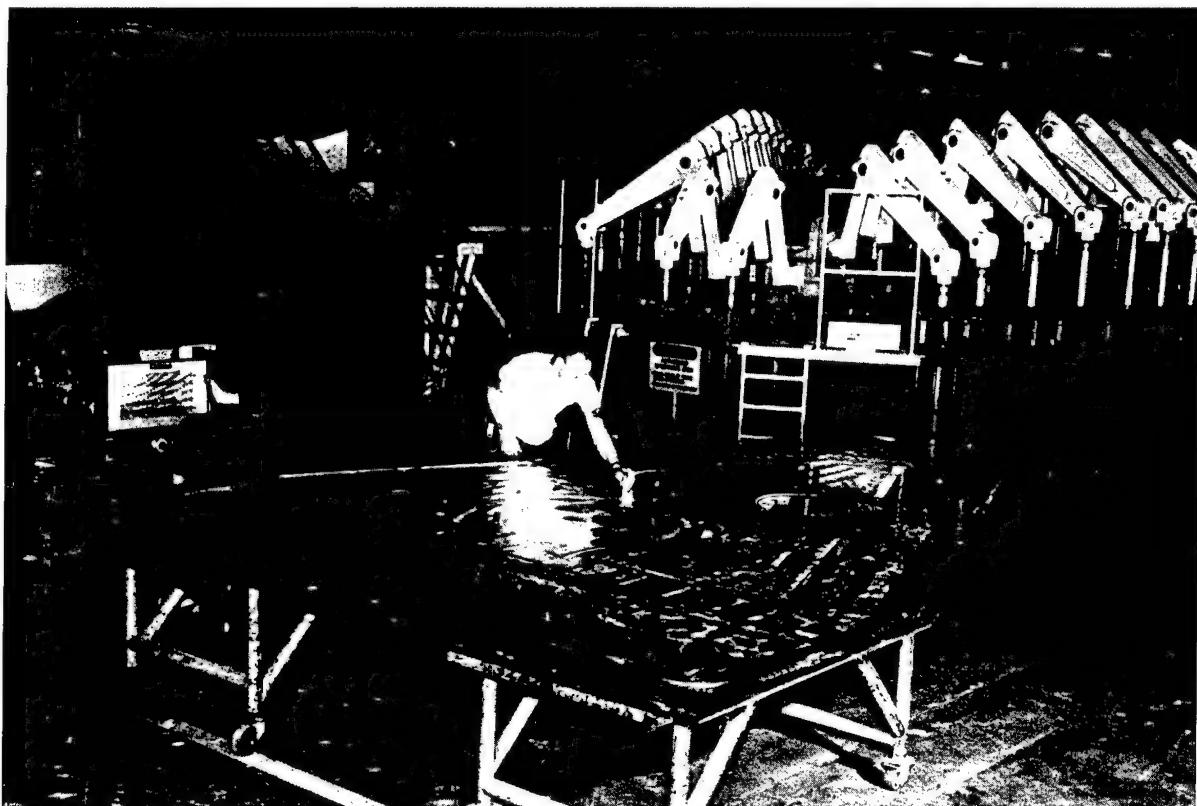
Figure 35.—Presculptured apex gore and hydro-bulging machine for it.

location of weld lands and bosses. The variables in the process are: (1) pressure of side clamps, (2) pressure of end clamps, (3) controlled slip of the part between the clamps, (4) forming pressure, and (5) presculptured dimensions.

Usually only two blanks are used to establish different combinations of the variables for development of the production-process technique. Some blanks, especially those that are thinner, must be permitted to slip into the cavity where they are then stretched to the final shape. This is accomplished by proper use of aluminum alloy and Teflon shims placed along the surfaces that must be gripped to prevent distortion. The Teflon acts as a dry lubricant and prevents galling.

In order to measure the slippage, a hole is drilled on the edge that elongates. After the die cavity is sealed, the part is bulged until the hole has moved the desired distance toward the die, indicating the proper slippage. The pressure is then released, all shims removed, and final forming is accomplished by gripping and holding the blank all around and stretching the material into the contour of the die.

Some gores have holes cut at locations where fittings are to be welded. This of course allows the material around the holes to stretch more easily. These holes are cut to a developed elliptical shape, purposely made undersize, which stretches to the desired round opening during the process. The resultant openings are later machined to the required diameter. The holes are plugged with metal plates and seals during forming so that the forming fluid will not leak through the opening. Figure 36 depicts the contractor's typical forming procedure.

Actual forming time of the gores in the dies varies from 30 minutes to 2½ hours, depending on the configuration of the blank.

In regard to the development work in hydraulic bulging of the 54-inch diameter center pieces, the contractor proceeded as follows upon receiving the die. Having had the MSFC experience in hydraulic bulging the center pieces of 2219-T87 alloy, the contractor first free-formed four pieces to the depth of 2.60 to 2.80 inches using 2219-T37 alloy. The parts came out slightly warped and deeper than necessary. It was agreed, however,
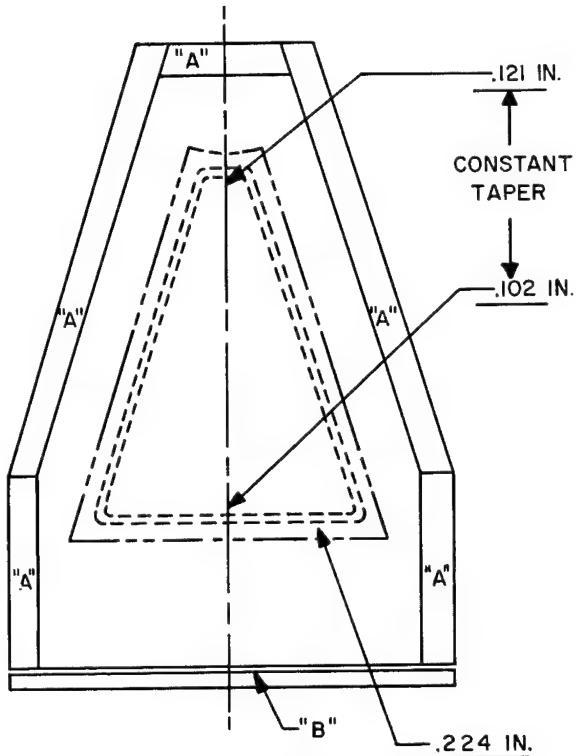
Figure 36.—Typical gore-forming procedure.

60B24107-1 Gore apex-S-IC-S
No fitting — upper head — fuel tank

Recommended procedure

A. Machining
Machine part per engineering using thinout and elongation information gained by TMLO from formed sculptured parts. Use shims to control thinout. (K&T Machine.)

B. Forming
1. Apply grid lines and Vidigage.
2. Lubricate outer surface and apply clay balls.
3. Allow draw on bottom or wide end using following method:
   (a) Apply shims 0.032 in. $\times$ 4 in. wide 2024-T both sides of part in area "A."
   (b) Remove 1½-in. wide strip from bottom of part in area "B."
   (c) Drill ⅛-in. dia. hole in center of 1½-in. strip (area "B") for measurement of feed-in.
   (d) Install 1½-in. wide strip with 0.032 in. $\times$ 1½-in. wide 2024-T shim, both sides of strip (area "B").
4. 1800 psi minimum clamping pressure all cylinders.
5. Apply water pressure until indicator rod at area "B" shows a draw on 1⅛ in. Raise upper die member and remove all 0.032-in. thick shims.
6. Apply 450 psi minimum water pressure.

C. Checking
TMLO check part as necessary for deviation from engineering (for tape correction and thinout shim adjustment).

NOTE: The above procedure applies to 60B24107-1 only.

that the formed parts could be brought into the correct contour by age sizing them to the T87 condition in a proper heat-treat fixture.

Such a fixture was fabricated and, after the center hole was cut and preliminary edge trimming was accomplished, the parts were aged on the fixture in an oven to the T87 condition. After final edge trimming, the parts came out very close to the required contour, deviating only 0.08 to 0.10 inch at the center hole.

The plastic insert of the bulge-forming die was then remachined to a 150-inch radius, 2.50 inches deep, and the die was released for parts fabrication. Using this die and the heat-treat fixture, parts were successfully hydro bulged and age sized in the two required thicknesses of 0.224 and 0.359 inch.

AGE FORMING AND SIZING

Age forming is a new technique, developed by a contractor under the sponsorship of the MSFC Manufacturing Engineering Laboratory. Using this technique, flat presculptured or constant-thickness aluminum alloy panels are restrained on a fixture of a required radius and heat treated or aged at a specified temperature for a prescribed period of time. During the time the part is being aged, the material yields to the stress induced by the action of holding it in the fixture while precipitation hardening takes place in the metal. This locks the metal in the restrained contour and thus forms the radius. However, upon removal from the fixture, the developed radius in the part will not be equal to the fixed radius of the fixture as there will be a spring back of approximately 23 to 25 percent for 2219-T37 aluminum alloy.

In developing this process, the contractor originally experimented with small panels of 2219 aluminum alloy, ranging in size from 4 by 18 inches to 16 by 18 inches, and in thickness, from 0.497 inch to 0.600 inch. Some panels were presculptured, others were plain, constant thickness, and all were in T87 age-tempered condition. These experiments could be classified as "creep forming" because the material was already in the aged condition.

The panels, one by one, were uniformly prestressed up to the yield point on a 65-inch-radius fixture and exposed to various temperatures for different periods of time. The temperatures ranged from 250° to 350° F, and the duration of exposure ranged from one to eight hours. The

results of these experiments were not entirely satisfactory for the following reasons: (1) the spring-back was on the order of 65 to 67 percent, (2) there were losses in mechanical properties on the order of 4 percent in the ultimate strengths and 7 percent in the yield strength of the original values for the T87 material. However, it was determined that the presculptured "cut-outs" had no apparent effect on the developed radius and there were no flat spots or bulges.

Two panels with cut-outs were grid-lined on ½-inch centers and the chord heights measured at the points of grid line intersections. Then, using the "circle-through-three-points" method, the chord heights for true radii were computed. The measured and computed chord heights agreed exactly or varied insignificantly, indicating that the developed curvature was a true radius and that there were no flat sections at the ends.

The next set of experiments was performed by the contractor on 16 sub-scale panels, approximately 1⅛ inches thick. Eight panels were 32 by 98 inches, and the balance were 50 by 122 inches. All material was 2219 aluminum alloy in T37 solution, heat-treated, and cold-worked condition. Full-scale quarter panels for Saturn V, S-1C stage propellant tanks require 2¼-inch thickness and are approximately 10 feet by 26 feet in size.

All of the experimental panels were machine-milled with integral stiffeners to simulate the full-scale quarter-panel tank skins. One-half of the panels were machined with stiffeners parallel to the long dimension of the panels, the other half with stiffeners transverse to the long dimension of the panels.
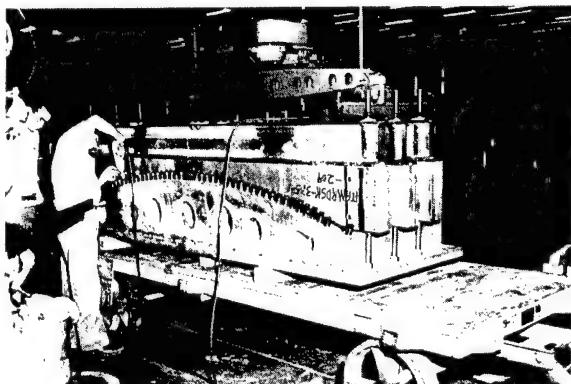
Figure 37.—Age-forming fixture for panel with transverse stiffeners.
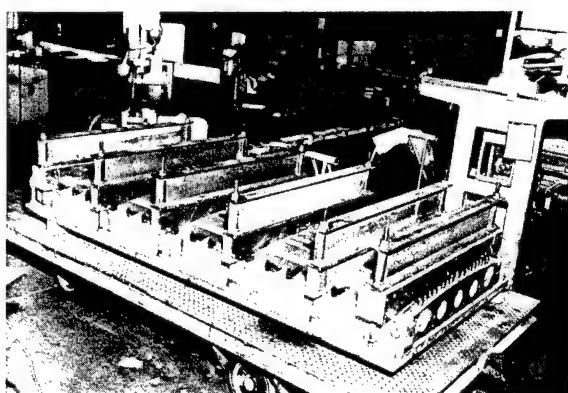
Figure 38.—Age-forming fixture for panel with longitudinal stiffeners.

The purpose in preparing these panels was to obtain research results of age forming the panels into the 198-inch radius measured to the outside diameter of the full-scale tank. Accordingly, the two age-forming fixtures were designed and fabricated, one for each size of panel, as illustrated in figures 37 and 38. The age-forming radius generated in the female headers of the fixtures was 143 inches. Several thermocouples were attached in various locations, both to the fixtures and to the panel being age formed, as well as to the pull-test coupon, to monitor the temperature and time during the process.

The processing of the panels was started at 325° F and held for 14 hours. After the first four panels were thus processed, instructions were received to extend the time to 24 hours, in accordance with the latest recommendations of the material supplier. While retaining the original fixture-forming radius of 143 inches, three more panels were processed at 325° F for 24 hours each. The resultant formed radius, however, was too small, indicating the need to modify the fixtures. This was accomplished, making the forming radius 147 inches for the larger panel fixture and 152 inches for the smaller one. The difference in the radii was to serve as a guide for the age-forming fixture of full-scale panels.

The remaining nine panels were age formed on the modified fixtures at 325° F for 24 hours each, with good results.

The average calculated formed radius for these panels was 198.7 inches and average calculated spring-back was 24.6 percent. To calculate the values of the spring-back and lengths of the radii, measurements were taken of the chord length and

chord height for each panel. The following formulae were used:

$$R = \frac{4H^2 + L^2}{8H}$$

where H = chord height
where L = chord length

$$\% \text{ spring-back} = 100 - \frac{\text{average}}{\text{fixture radius}} \times 100$$

% spring-back = 100 — developed radius × 100

Two test coupons were processed with each panel and in each instance the mechanical properties of ultimate tensile strength, yield strength, and elongation were either equal or very close to the typical values outlined by the supplier for T87 condition: 68,000 to 69,000 pounds per square inch for ultimate strength, 57,000 pounds per square inch for yield and 10-percent elongation. All values were well above the minimum specification values recommended for design.

Investigation was made to determine the residual stress level on the age-formed panels of 2219-T87 aluminum alloy. The residual stress was measured by the X-ray-diffraction-pattern method. It should be noted that the residual stresses on both the convex and concave sides of the panels were compressive and rather low in values: 3000 to 4000 pounds per square inch for convex and 5000 to 4000 pounds per square inch for concave.

Two panels were cooled by water spray with cooling time of 30 minutes. All others were air cooled with cooling time of 8 to 10 hours. A study of the two panels cooled by water showed no warpage and no change in mechanical properties as compared to the air-cooled panels. Furthermore, a residual stress determination made on a water-cooled panel showed the stress level on the outside surface as zero pounds per square inch and on the inside surface as 3000 pounds per square inch compressive.

In contrast to these results, the T87 small sample panels, brake formed and roll formed to the same radius, showed residual compressive stresses on the convex side of 31,000 pounds per square inch and 18,000 pounds per square inch, respectively. The residual stresses were tensile on the concave side, 15,000 pounds per square inch and 17,000 pounds per square inch, respectively.

In age forming the panels, a change in dimensions occurs as a result of the aging mechanism and the forming of a radius. Both the lengthwise (axial) dimension as well as the arc (circumferential) dimension are affected. It appears that the axial dimension increases because of aging, while the circumferential dimension increases because of both the aging and the formation of the radius. The circumferential growth appears to be, in principle, a function of the material thickness and of the developed radius. The thicker the material, the greater the growth. An indication as to the amount of growth may be shown as: growth (g) = (thickness)/(2 × radius).

From the axial and arc measurements of some of the processed panels, it was determined that the total amount of growth is not large, on the order of $\frac{1}{8}$ inch in 10 feet axially, and $\frac{1}{16}$ inch in 4 feet circumferentially. However, the growth becomes important and the allowance for it must be made where a part to be age formed is machined to close tolerances prior to forming.

It was also observed that the radius developed in a panel is true, except for the last 2 inches at each end of the die. At these locations, there is a radius, but it is somewhat larger than the developed true radius. This condition is probably a result of the panel clamping difficulties.

Consequently, the trimming allowance has to be made on all four edges of the panels for growth and for a larger radii at the ends to provide a true contour over the full arc.

To summarize the results of experimentation with the 16-subscale 2219-T37 aluminum alloy panels, it can be said that:

1. Age forming of large radii, in irregular sections of 2219-T37 alloy aged to T87 condition, is practical and repeatable.

2. A tolerance of plus or minus 2 inches in age-formed panels of 198 inches nominal radius is reasonable for design purposes.

3. The residual stress level is low and is compressive on both the convex and the concave surfaces. This has a beneficial effect on the possible stress corrosion.

4. Age forming has no effect on the mechanical properties of the age-formed panels.

5. Water spray used to cool the panel and the fixture has no adverse effect on mechanical properties, residual stresses, or warpage.

6. In age forming, the panels yield as a unit; therefore, the developed radius is essentially a true radius. Also, sculptural areas, stiffeners, and the like on the concave side have little if any influence on the outer surface of the panel.

7. Age-formed panels increase in dimensions both axially and circumferentially. The growth is a function of: (1) the aging mechanism, (2) the developed radius, and (3) the material thickness.

8. The metal gain direction has an influence on the spring-back, the transverse gain direction has a greater spring-back.

9. Allowance for trimming should be made in panels for growth and for flatter ends.

As a result of these findings, the contractor is currently age forming the full-scale quarter-panel tank skins for the Saturn V, S-1C Stage, as shown in figure 39.

Further research experiments by the contractor in age forming 2219-T37 material to the T87 condition brought to light additional features of this process. Regardless of whether the material is ¼ inch thick or 1 inch thick, it will develop the same radius after age forming on the same radius fixture. Also, panels ¼ inch thick and 1

Figure 40.—Lower portion of the gore age-sizing fixture.

inch thick, sandwiched together and aged on the same fixture at the same time, will produce essentially the same radius.

This led to experimentation with tapered parts on two panels, 6 by 18 by 1 inch thick, which were tapered lengthwise so that one end was 1 inch and the opposite end was 0.2 inch thick. These pieces were age formed as a pair to a radius of 120 inches. The resultant radius on the outer fiber was uniform and true and the two pieces matched perfectly. The second pair of 6-by-18-by-1-inch panels was tapered crosswise, that is, along the 6-inch dimension. In addition, the pair was sculptured on the inside. Once more these panels were age formed to the 120-inch radius on the outer fiber and again they matched.

In further experimental work, the contractor was able to successfully age form compound contours, such as a 24-inch-diameter circle over a 50-inch spherical radius and a truncated triangle with 24-inch sides to a compound curvature, like a sub-scale tank gore. The results, although encouraging, were not conclusive, and further investigation is needed.

Age sizing, the companion technique of age forming, is a means of correcting variations in contour of previously formed parts by aging these parts in the restraining fixtures. MSFC is currently using the age-sizing technique to remove distortions which occur when fittings are welded at MSFC into the Saturn V propellant tank gores, which are made of 2219-T37 alloy. Figure 40 shows the lower portion of the age-sizing fixture and figure 41 shows the upper portion of the fixture resting on a rack. It has been found to be


Figure 39.—Full-scale tank skin being placed into age-forming fixture.
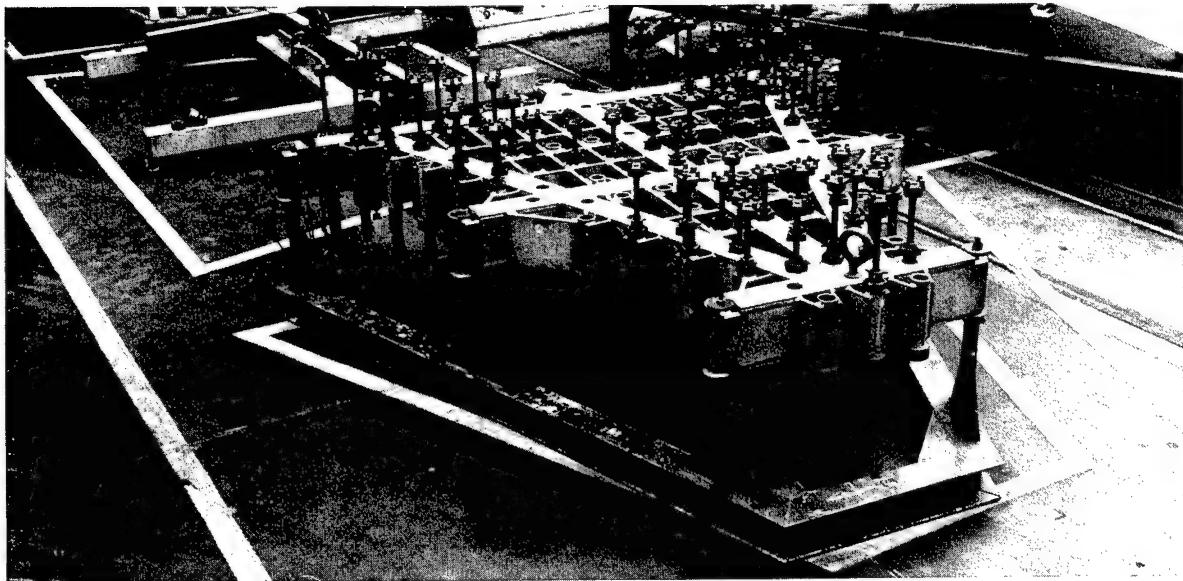
Figure 41.—Upper portion of the gore age-sizing fixture.
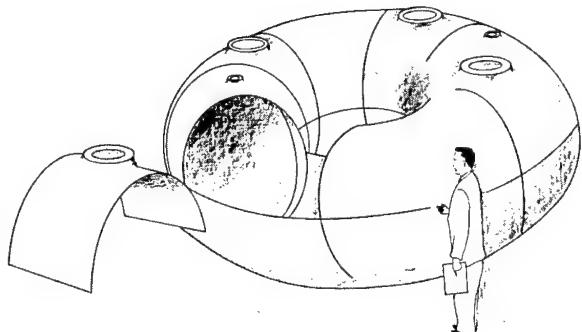
Figure 42.—200-inch diameter Torus test tank.

necessary to tighten the bolts in sequence, starting at the center and working outwards. Otherwise, any excess metal might produce buckling.

HOT-DRAPE FORMING

Hot-drape forming is a new technique which originated elsewhere, but which is presently in final stages of development by a contractor sponsored by the MSFC Manufacturing Engineering Laboratory. This technique is actually a combination of hot-stretch forming, die quenching, and age forming and is currently being used experimentally to form the skin sections for a 200-inch-outside-diameter TORUS test tank, as illustrated in figure 42.

The single male die is made of glassrock with six sets of independently controlled electrical heat-

ing elements set in the die to provide for the flexibility of the selective-zone temperature control. The temperature of the die is monitored by 24 thermocouples imbedded in the die surface, four to each set of heating elements. The face of the die is coated with boron-nitride, a high temperature lubricant. This lubricant, in serving two purposes, allows the work piece to slide more easily over the die surface while it is being stretched and also prevents scratching of the material. The need for a scuff sheet between the die and the work piece is thereby eliminated, thus providing better control of temperature uniformity over the entire area of the heated work piece.

The new 7039 aluminum alloy sheet material, in annealed condition, is held at both ends in a vertical stretching machine by specially designed jaws, illustrated in figure 43. The die is heated to approximately 600° F, and the material is wrapped around the die. As tension is applied on the jaws, the stretching of the material is closely watched. By observation, the operator determines which heating elements are to be turned off or on to decrease or increase the yield of the material in a particular zone.

When forming is completed, the tension on the jaws is slackened only enough to stop stretching, but remaining sufficiently tight to keep the material snug on the die. The heating of the die is increased to the solution heat-treatment temperature of 880° F. The pair of insulating doors
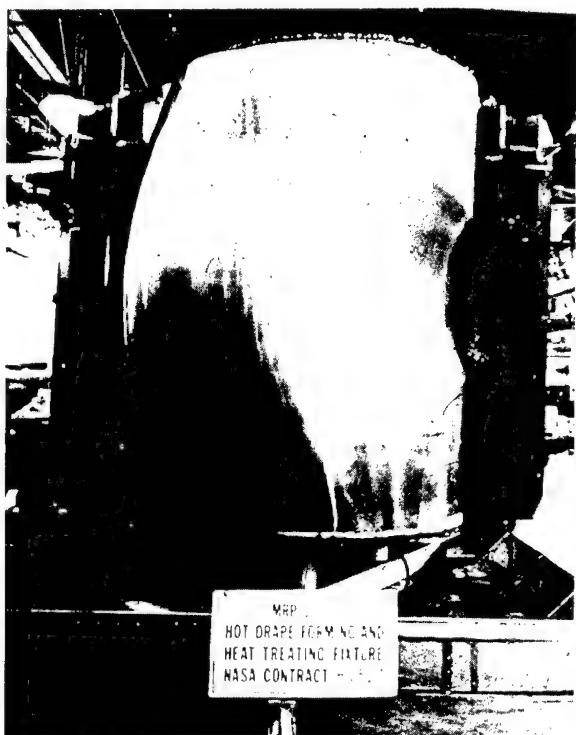
Figure 43.—Torus test tank skin segment being formed.

provided are fashioned from a rejected skin and insulated with 3-inch-thick fiberglass. These doors, hinged to the die fixture, are now positioned close to the heated skin to reduce heat radiation losses from the skin surface. The die and the skin are kept at a temperature of 880° F for the required length of time, after which the heat is turned off. Then, with the aid of a special spray hood, the skin is water quenched on the outside at a prescribed rate. The skin is then backed away from the die and water spray is directed to the surface of the die to prevent it from reheating the skin.

For aging, the skin is brought back in contact with the die, the electric heat is turned on again, and the temperature of the skin is raised to the degree required for aging. The temperature is held at this point during the specified number of hours, after which the heat is turned off and the skin is allowed to cool to room temperature. The 7039 alloy is then in the T63 condition. The part is removed from the jaws and is ready for rough trimming and inspection prior to shipment (fig. 44).

Currently, development work is being carried on with water-quenching rate, aging temperature,

and time in order to assure the required mechanical properties of the T63 condition.

EXPLOSIVE FORMING

The use of explosives to perform useful work on metals goes back to the 19th century. A British patent issued in 1897 made reference to most of the technique variations as used today, but the ideas attracted little attention and were largely ignored for nearly 40 years. The lack of interest in explosive forming during its early stage of development was probably because of a lack of apparent advantage over conventional methods in fulfilling the metal forming requirements of the time. However, in the early 1930's, explosive forming was used for the shallow cupping of heavy steel plates for ordnance adaptations. During the past decade, the aircraft and missile industries mainly have turned to the explosive working of metals because they have been faced with new requirements which exceeded existing press capacities. The problem areas have been associated with higher strength and heavier gage materials, closer tolerances, intricate shapes, and short runs of large size parts.

Most explosive metal-working operations can be considered as falling into one of two general groups, depending on the location of the explosive charge relative to the work piece. In the first group, known as contact operations, the charge is placed in intimate contact with the work piece so that the explosive energy acts on the metal directly. Most of the contact operations include welding, hardening, controlled cutting, and powder compaction. In the second group, classed as standoff operations, the charge is located some
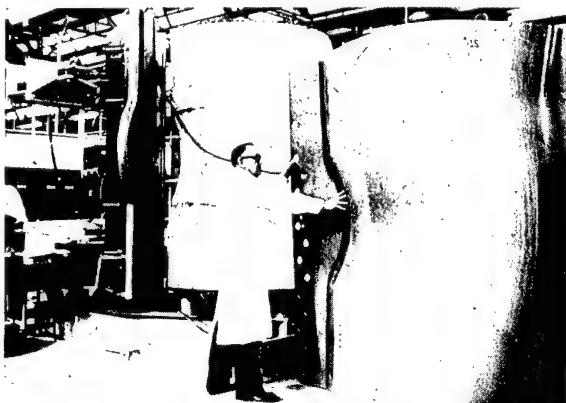

Figure 44.—Torus test tank skin segment formed and heat treated.

distance from the work piece and the explosive energy is transmitted to it through an intervening medium such as air, oil, or water. The concern here is with only those operations in this latter group as they are used mainly for sizing and forming of parts.

In explosive forming, also known as high-energy-rate forming, a metal blank is placed over a die cavity, air is evacuated from under the blank, and a high-intensity pressure pulse of very short duration is produced by exploding a predetermined charge at a suitable distance from the blank. The process is usually performed in a tank which is set in the ground and filled with water. When the configuration of the part permits, the free forming or dieless forming technique is used.

While the pressure pulse can be produced by either a chemical explosive or an electrical discharge, the discussion here will be confined to the chemical explosives. This method is considered preferable because of the relatively low capital investment required.

Many types of chemical explosives, possessing a wide range of properties, are available for metal-forming operations. Generally, the explosives can be classed as high explosives and low explosives, both classes being used in metal-working operations. A high explosive is typified by TNT, PETN, or dynamite. Common examples of low explosives are smokeless powders and black powders.

The energy conversion time for high explosives is measured in microseconds, while that of low explosives is measured in milliseconds or greater. The rate of detonation of high explosives ranges from 6000 to 28,000 feet per second approximately, and the rate of deflagration of low explosives is from a few inches to a few feet per second. The pressures produced by high explosives at the surface of the charge are on the order of 2,000,000 to 4,000,000 pounds per square inch. Low explosives produce pressures on the order of about 40,000 pounds per square inch.

To transmit the pressure pulse (shock wave) to the blank being formed, water is usually employed rather than air. Water, being practically non-compressible, will transmit the force of explosion more efficiently and uniformly to the entire area of the blank. Water also has another advantage in that it muffles the sound of the explosion and provides safer operating conditions for personnel.

Tanks are usually fabricated from welded steel plates, with the wall thickness varying from ¼ inch to 1¼ inch, depending on size and material of parts to be formed as this governs the size of tank and weight of the explosive charges. Tank sizes range from 3 to 30 or more feet in diameter and from 3 to 15 feet in depth.

To reduce strain in the tank wall and base resulting from relatively large charges, some tanks have an air cushion of coiled hose under the base and double walls filled with pumice or rubber.
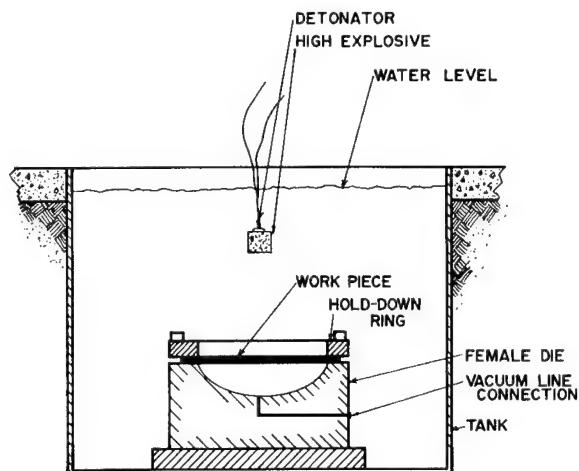
Figure 45.—Typical explosive-forming technique.
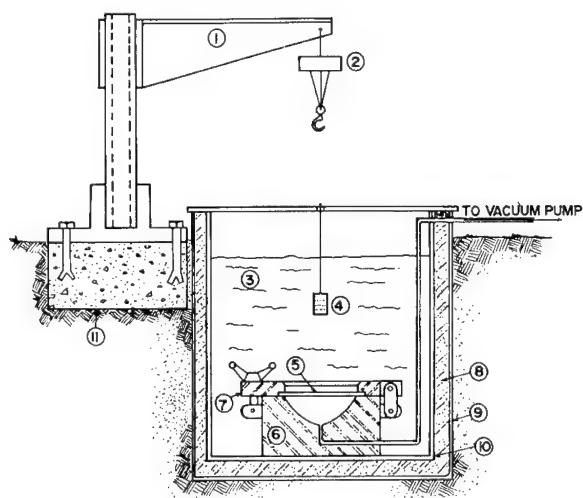
Figure 46.—Explosive-forming installation.

1. Rotating beam
2. Winch
3. Water
4. Explosive
5. Blank
6. Die
7. Pressure ring
8. Rubber
9. Thin-walled outer tank
10. Steel tank made of heavy boiler plate
11. Concrete

Others have a flexible seal between the base and the wall which allows the tank wall to expand during the forming operation. Tanks with single wall construction sometimes have an aerator manifold on the bottom inside the tanks, thus providing an air bubble curtain during actual operation to reduce strains in the tank walls. A typical explosive-forming operation is shown schematically in figure 45. A variant of an explosive-forming installation with a die-handling facility and a double-walled tank is illustrated in figure 46.

For some specific applications, especially for out-sized parts, explosive forming offers definite economic advantages over existing mechanical forming techniques. The source of energy used is inexpensive and almost unlimited, and the tooling expenditure is minimized because only the female part of a die is needed.

During the last several years, experience accumulated by the industry allowed for establishment of numerous guide lines for explosive forming, including formulae for determination of the required forming pressure and clamping force as well as nomograms for selection of the charge size and the standoff distance. Such aids naturally serve to minimize the uncertainties in explosive-forming operations; nevertheless, a new part to be explosively formed often presents numerous problems that must be resolved before a satisfactory forming process can be achieved.

Among these problems are the design and the material for the die, including draw radii and vacuum sealing. Suitable blank-clamping arrangements to permit an appropriate proportion between blank drawing and stretching must be made since, with total blank restraint, there could be excessive material thinout.

Dies are usually cast and machined from Kirksite, ductile iron, or steel. For short runs and light gages, however, the dies could be made of reinforced epoxy plastic or concrete faced with reinforced epoxy. Other problems include eliminating surface pitting on formed parts and minimizing spring-back. Experiments performed at Marshall Space Flight Center Manufacturing Engineering Laboratory indicated that surface pitting is definitely affected by the size of the charge and the standoff distance. Foreign matter or air bubbles on the surface of the blank could also produce pitting. This facult can be significantly reduced by eliminating air adhesion on the part surface through the use of precleaning techniques and wetting-agent additives and by the removal of foreign matter from the water. Pitting can be eliminated by the use of evacuated cover materials such as a rubber blanket. In regard to spring-back, controlled slight overforming would seem to be one logical answer.

Ofter testing of sub-scale samples is necessary to facilitate the solution of explosive-forming problems. Scaling laws have made it possible to use sub-scale parts for determining usable parameters which can be extrapolated to full-scale parts.

It was decided at MSFC to investigate the possibility of explosively forming the tank bulkhead center pieces to develop process information applicable to forming full-scale apex and base gores for propellant tanks of the Advanced Saturn V, S-IC Stage. The gores measure 144 inches by 210 inches for apex gore, and 115 inches by 230 inches for base gore. They vary in thickness from 0.195 inch to 0.830 inch. The center pieces are 54 inches in diameter and also vary in thickness. Those formed at MSFC were 0.312 inch thick.

A concave die was designed, cast in Meehanite iron, and machined to the net contour of the part, with a maximum depth of 1.312 inches. The die had an opening for drawing a vacuum under the blank to allow full blank-to-die contact and was equipped with a draw ring, held in place by twelve ¾-inch-diameter bolts.

A total of nine blanks was prepared from 0.312-inch thick 2219-T87 aluminum alloy. The blank to be formed was placed over the die cavity, the draw ring bolted in place, and a vacuum drawn. The PETN explosive Primacord charge was positioned above the blank by means of a wire grid. A blasting cap was attached to the charge, the assembly lowered into the tank, and charge detonated. The part was then removed for examination and the contour was checked with templates. This procedure was repeated as required to complete the forming. The arrangement is shown in figure 47.

Exceeding the high elastic limit (57,000 pounds per square inch) of the T87 material by tensile loading during forming proved to be a serious problem since the required part contour was very shallow; efforts were concentrated, therefore, on accomplishing the final forming by application of pressures in excess of the compressive yield strength of the material.

With the standoff distance varying from 2 to 6
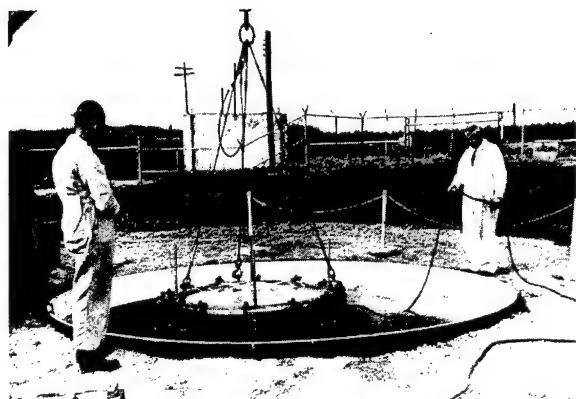
Figure 47.—Explosive-forming setup.

inches (mostly 4 inches), the charge was increased gradually from 700 grains (1/10 pound) to 16,100 grains (2-3/10 pounds). In one case, the charge consisted of 1½ pounds of composition C4, with a standoff distance of 19½ inches. A total of 31 detonations was made. Some blanks were struck only once, others several times.

The results of forming efforts on the nine blanks were varied. There were some partial misfires when the spacing between Primacord loops was less than 3 inches, which resulted in severing of the Primacord in front of the burning explosive. Maintaining a wider spacing eliminated such occurrences.

The degree of forming was proportional to the size of explosive charge, but several parts were underformed and two parts were overformed. Grain direction was also found to affect resultant contour. A consistently greater degree of forming was noted parallel to the direction of grain flow.

Three parts were restruck after trimming and chemical milling to a nominal thickness of 0.230 inch. Prior to restrike, the blanks were covered with a 0.312-inch-thick aluminum alloy cushion which produced a significant improvement in resultant contour. One part, of the last three, was preformed by hydraulic bulging. This part formed to the template.

The experiments were terminated when cracks appeared in the form die. Metallurgical analysis revealed that the failure was primarily a result of the fact that the casting was understrength.

Pursuant to the original project of developing S-1C-Stage gore-shaping technology, an additional series of tests was conducted at MSFC to compare

results of explosive draw forming versus explosive stretch forming.

An explosive form die, spherically radiused, 50 inches in diameter, and 7.25 inches in depth, was chosen from available tooling. This die simulated the required condition of shallow contour and was of sufficient diameter to minimize error in extrapolating test results to large components. Also, a minimum of tool modification was required to incorporate the provision for total restraint of the blank. From the results of previously accomplished experiments, it was determined that a thickened blank, edge loaded in shear, provided a simple method of blank restraint for use in a test program.

The selected test material was 2219 aluminum alloy in the T37 temper. The minimum elongation of this alloy and temper is 6 percent and forming conditions were controlled so as to remain within this guaranteed allowable. A dimensional evaluation was conducted on all formed parts and was repeated after trimming to final dimensions.

Figure 48 schematically shows the set-up for explosive draw forming of the two 60-inch-diameter 0.250-inch-thick blanks. Zinc chromate tape was placed under the blank edge to seal the die cavity. The clamp ring was held in position by 12 clamps secured with 1-inch-diameter stainless steel bolts tightened to 400 foot-pounds of torque. A vacuum was drawn under the blank and an explosive charge was placed above it. The assembly was lowered into the forming tank, and the charge was detonated. The procedure was repeated as required to form the part. Forming was terminated when die impressions left on the outer surface of the blank revealed that complete contact had been made.
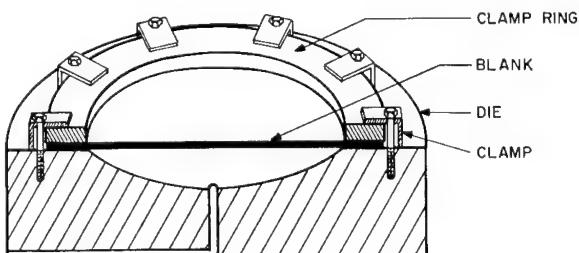

Figure 48.—Test arrangement for explosive draw-forming evaluation.

Figure 49 schematically illustrates the arrangement for explosive stretch forming of the eight

55-inch-diameter blanks. The original thickness of the blanks was 0.500, 0.750, and 1.000 inch. The centers of the blanks were removed by milling, leaving the original thickness as a restraining flange. The width of the restraining flange varied from test to test, although a minimum flange width of 1 inch was required to prevent shear failure. Attempts were made to vary the percentages of stretch and draw by changing the distance between the restraining flange and the outside diameter of the restraining ring.
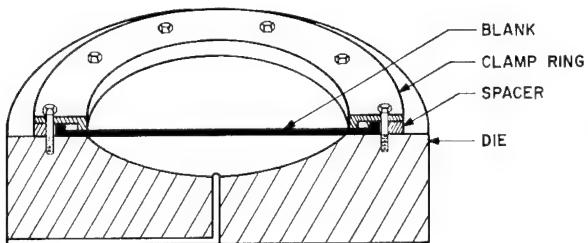

Figure 49.—Test arrangement for explosive stretch-forming evaluation.

Three blanks had the centers machined to a thickness of 0.500 inch while the remainder had the centers machined to a thickness of 0.250 inch. A machined spacer was placed around the perimeter of the blank to provide support for the heel of the clamp ring. The balance of the procedure was the same as that described in the explosive draw forming operations.

A total of 49 detonations was made, with Primacord charge size varying from 600 grains to 7600 grains and the standoff distance varying from 6 to 20 inches. In one case, 1 pound of composition C4 was used with a standoff distance of 24 inches. Some blanks were struck only once, others several times. The results of these tests were very encouraging and demonstrated the feasibility of explosive stretch forming 2219-T37 aluminum alloy parts.

Although there were instances of restraining-flange failures in shear, and the clamp ring had to be replaced in the middle of the tests because its flange was partially torn off, successful results were obtained with three blanks.

The amount of the blank stretching was on the order of 3 to 4 percent, both for 0.500- and 0.250-inch thickness.

In two cases, the average contour deviation from the template was approximately 0.1 inch

after forming. In the third case, the average contour deviation was 0.016 inch in one direction and 0.175 inch in the 90-degree direction.   This is attributed to upsetting of the restraining flange which occurred over an approximate length of 3 feet and allowed the flange to draw in slightly on the last strike. The change in contour, after trimming of the restraining flange, was minor in all three cases. Figure 50 shows a successfully stretch-formed 0.500-inch-thick part in the die. Figure 51 shows the contour check with a template on the same part after its restraining flange had been trimmed off.
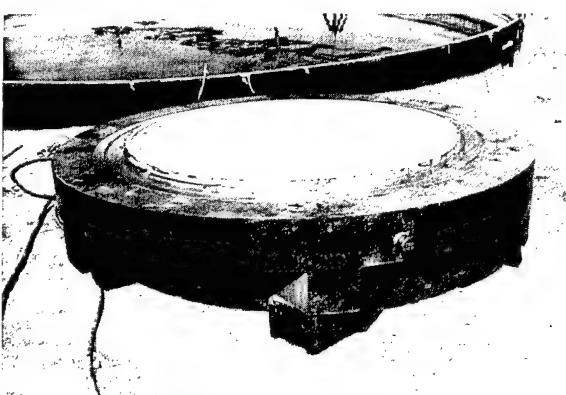
Figure 50.—Formed test part number three in die (clamp ring and spacer removed).

Figure 51.—Contour check, test part number three after trimming.

The two explosive-draw-formed blanks, as outlined previously, had no restraining flange, and no attempt was made to restrict movement of the blank other than to control wrinkling by confining the flange between the flat clamp ring and the die face. These parts exhibited 1.6-percent stretch and 4.1-percent draw. The contour deviations were approximately twice those of the stretch-

formed parts after forming, and considerable change in contour was noted after edge trimming.

Based upon results of these tests, it can be said that there is a definite improvement in the dimensional characteristics obtainable with explosive stretch forming as compared to those obtainable with explosive draw forming. Also, in the interest of saving machining time and minimizing material loss, it would be advantageous to use a serrated or beaded clamping ring and die flange to provide a means for restraining the blank edge. Contour correction, for the parts formed by explosive stretching from 2219-T37 aluminum alloy, can be obtained by heat treatment of the part to the T87 condition in a restraining fixture.

A contractor, sponsored by MSFC, is developing the procedure for explosive stretch forming of the full-scale apex and base gores for propellant tank bulkheads of the Saturn V, S-1C Stage. Gore blank dimensions and thicknesses were mentioned previously.

The dies used by the contractor are composed of massive-ribbed steel castings with a minimum thickness of 7 inches at any point. Two holes are provided at the bottom of the die to draw a vacuum under the blank. Around the outer edge is a slot where the vacuum seal is placed.

The blank-clamping fixture has numerous, massive C-clamps, hydraulically operated, and supplemented by several gripper jaws around the die periphery to provide the high restraining forces needed for the flanges of the heavy blanks. Construction of the jaw is shown in figure 52.

A series of at least four shots is required to form an apex gore segment. The charge size of Primacord varies from 2400 grains to 10,800 grains. For the first two shots, a piece of 4-inch by 16-inch DuPont sheet explosive is added to each charge. The standoff distance varies from 12 to 30 inches.

After each shot, the clamp ring, die, and vacuum system are inspected visually. The forming pressures are on the order of 50,000 pounds per square inch or less as higher pressures could result in tank or die failures. A neoprene rubber blanket is used to protect the material surface against pitting. Figure 53 shows the explosive stretch-forming die with the clamping fixture for the apex gore. The massive size of the equipment required in this case can be appreciated from study of the illustration.
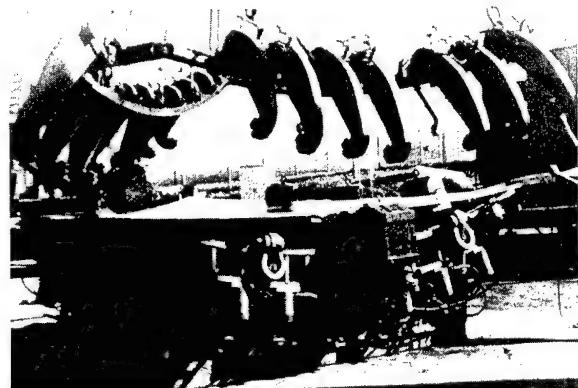
Figure 53.—Explosive stretch-forming die with apex gore blank.

Another contractor, also sponsored by MSFC, is successfully forming all the propellant tank gores of the Saturn V, S-II Stage. There are two types of gores, the "thin" apex gores and the "thick" base gores. The apex gores are uniform in thickness while the base gores have a tapering ribbed waffle pattern machined on the inside surface, with overall thickness varying from 1 inch to 1.830 inch. The material in this case is aluminum alloy 2014 in the T451 condition (stretch stess relieved).

Figure 52.—Stretch-press type gripper jaw construction.

Dies are made of massive 6-inch steel plate that was incrementally formed to approximate contour and welded to a supporting framework. The dies were then accurately machined to the desired final configuration and polished to mirror brightness. Steps are taken to preserve the brightness before each shot and between shots. Dies have a PVC O-ring for vacuum sealing the blank, and numerous screw type C-clamps to hold the draw ring in place. For forming, the screws are tightened to 600 foot-pound torque.

In forming apex gores, a ½-inch-thick blanket of epoxy urethane plastic is used over the blank to protect the material surface against pitting. The entrapped air is removed from between the blanket and the part through air hoses at the cor-

ners of the blanket. The area beneath the blank is purged with dry nitrogen to prevent possible burning of the blank by the heat generated during forming in case small amounts of oxygen are present.

Following the purging, a vacuum of 28 to 29 inches of mercury is drawn, and a Primacord explosive charge, specially shaped (for each shot) and tied to a nylon fish net, is attached to the standoff device. The arrangement, ready for the tank, is shown in figure 54. The entire assembly is then lowered into the tank where the charge is detonated.

All apex gores are normally hit twice while they are in the annealed temper, then heat-treated and quenched to the -W temper. They are hit a



Figure 54.—S-II Stage apex gore ready for water-tank immersion.

third and final time before being heat aged in a restraining fixture, and then chem-milled. The part is removed from the die, cleaned, and inspected after every shot. Standoff distance varies from 16 to 24 inches for different shots.

The thick waffle gores are formed in a similar manner except for a few important differences. To prevent buckling of the edges, a ripple-barrier rib is machined into the blank around the periphery and outside the final trim line. This rib is removed after forming is completed and before the part is heat aged in a restraining fixture. To support the waffle ribs during forming, the gore blank is sprayed with a vinyl parting agent, and the waffle cavities are filled with cerro-bend.

After the first forming operation, the cerro-bend cracks and must be removed and replaced. For removal of the cerro-bend, the gore is placed under a steam hood with convex side upward. The steam releases the cerro-bend, and it falls into a tray beneath the gore. This operation is performed after each of the three explosive shots. The stand-off distance is 20 inches for the first shot and 15 inches for the last two shots.

The last explosive operation is performed on the overform die without the draw ring, vacuum being the only hold-down employed. Conformity to contour is checked by placing dabs of zinc chromate paste in the bottom of the die and lowering the part onto it. The ripple barrier is removed and the part is then heat aged in a

Figure 55.—S-II Stage waffle base gore, explosively formed.

restraining fixture to an over-contour mold line to allow for spring-back to nominal contour. A formed waffle gore is shown in figure 55.

All gores are inspected for contour adherence on contour checking fixtures, using partial vacuum as a hold-down.

Because the gores explosively formed by both contractors are made of aluminum alloys 2219 and 2014 and are subject to corrosion, great care must be taken to protect the surfaces of the parts during the cycles of fabrication or storage. This is usually accomplished by applying a chromate conversion coating.

ELECTROHYDRAULIC FORMING

The electrohydraulic metal forming (EHF) technique is essentially a high-energy-rate forming method, wherein metal displacement is accomplished by a shock wave and an after-pressure pulse in liquid. The shock wave is generated by an ultra-rapid discharge of a high-amplitude electric current from a capacitor bank into two electrodes, also immersed in the liquid. The intensity of the shock wave is readily controlled by the amount of stored energy applied to the capacitors.

In regard to the liquid used as an energy transfer medium from electrical discharge to forming of metal, a contractor, sponsored by MSFC, investigated various liquids and concluded that ordinary tap water is about the best, all things considered. Methyl chloride and glycerine showed somewhat higher forming efficiency, but the dissociation odors and messiness outweighed the efficiency advantage.

As in chemical explosive forming of flat material to a desired contour, the blank is held in a female die by a draw ring. The die cavity is evacuated and the assembly is lowered into a tank filled with water. The electrodes or the forming head are also lowered into the water and set at a predetermined distance from the blank. The charged capacitor bank is then discharged into the electrodes or the forming head. A resultant shock wave and a pressure pulse forces the blank into the die to complete forming operation. The shock wave originating between the electrodes can be set up either by a spark discharge across the electrodes or by an exploding wire bridging the two electrodes. Spark discharge creates high intensity plasma between the electrodes and vaporizes a thin channel of water, expanding it
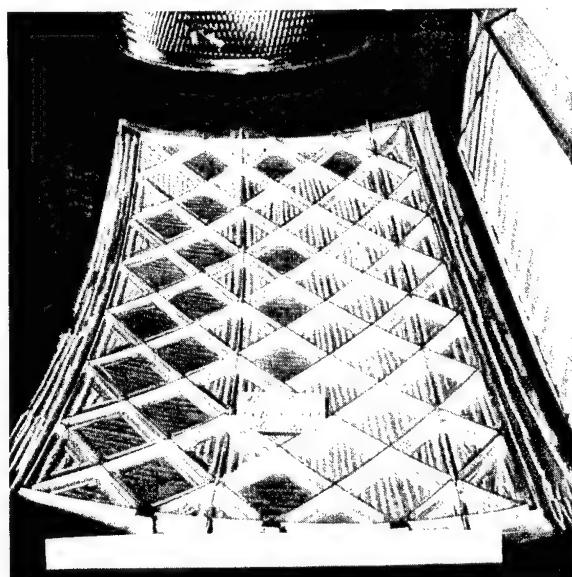
so rapidly that a shock wave is produced. The wire, bridging the electrodes, explodes under the high current discharge and starts the shock wave.

Theoretically, spark discharge systems have no limit in energy capacity and forming of parts can be done inside a plant. However, the cost and the size of the capacitor bank generally limit the energy capacity of the installations to practical dimensions. A 1-megajoule bank, for example, would occupy about 2500 square feet of floor space.

Early electrohydraulic forming tests, performed at MSFC by the Manufacturing Engineering Laboratory proved conclusively that using an EBW (exploding bridgewire) across the electrodes in the liquid greatly improves the efficiency of energy conversion from capacitor-stored energy to useful metal-forming work. The EBW technique also provides reproducibility and permits pressure-yielding discharges at lower voltage and energy levels. The efficiency of conversion of electro-static stored energy in the capacitors to useful metal-forming work depends mainly on the fluid pressure produced by the shock wave. Pressure measurements performed at MSFC in the vicinity of the bridge-wire have shown that the pressure attenuation is exponential with distance. This indicates that, when forming in a relatively un-confined arrangement such as a large pit or chamber, it is necessary to position electrodes and bridgewire reasonably close to the work.

Actual figures obtained near EBW plasma were on the order of 42,000 pounds per square inch at a distance of 6 centimeters from a discharge of 130,000 joules through a 0.062-centimeter titanium bridgewire across a 2-inch gap, using tap water as the shock-transmitting medium. At closer distances, pressures on the order of 100,000 pounds per square inch or even greater are possible. It has also been found that at the higher energy levels, pressure apparently increases exponentially with charge voltage on the capacitor bank.

The overall efficiency of conversion of electro-static energy to useful work generally ranges from 10 to 30 percent or more. In chambers where the plasma is relatively unconfined by chamber geometry, efficiency near the 10-percent figure is more common. However, in closely confined geometries, efficiency approaching 30 percent is quite frequent.

At MSFC it has been found that, in forming

small parts, placing the exploding bridgewire at the apex of a cone, which constitutes a closed chamber filled with water, gives tremendous increases in forming efficiency by utilizing the principle of the noncompressibility of water (fig. 56). On the other hand, in the forming of large parts (40 to 60 inches in diameter) requiring many shots, 2- to 5-percent efficiency would be more realistic.
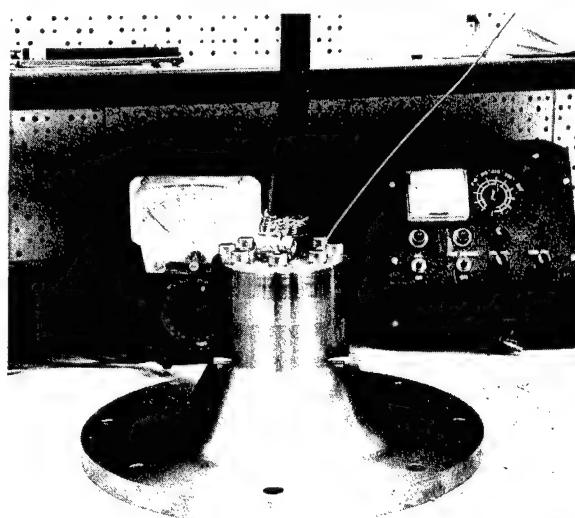
Figure 56.—Conical shaping head.

While forming efficiency is a complex function of many system parameters, it has become more apparent that a well-designed low-inductance system with a characteristically fast rise time is a much more efficient "shock-wave generator" than is the high inductance, slower discharge system. A high-inductance, slow-discharge circuit generally produces high dissipative heat losses, a condition not conducive to useful forming of metal. On the other hand, a low-inductance, fast-discharge circuit increases the no-load frequency of a capacitor bank and produces higher instantaneous discharge power for a given energy level.

It appears also that the shock wave does most of the useful work and that the oscillating "after pressure pulse" is of secondary importance in the forming operation. Many tests of this type have been executed in a 7-foot diameter by 8-foot deep test chamber at MSFC, using the 240,000-joule "Medusa" capacitor bank as the power source.

The original electrohydraulic forming equipment at MSFC was of 24,000-joule capacity. The system is schematically shown in figure 57 and consists of the following:

Main bank capacitors: eight Dubilier low-inductance, fast-discharge type, connected in a parallel plate construction, providing 120 microfarads at 20 kilovolts, and mounted in a mobile frame.

Trigger capacitors: 3 to 4 microfarads each, charged to 3500 volts.

Switching system: ionization-type switch utilizing pulse-type initiation by means of a spark plug and auxiliary trigger capacitors.

Transmission line: coaxial cable No. RG-17/u

to provide low-inductance current-carrying capability.

Main bank power supply: beta supply, delivering 150 milliamperes at 20 kilovolts.

Trigger power supply: Chicago condenser type, delivering 5 milliamperes at voltages up to 15 kilovolts.

Vacuum system: Kinney 8 cubic foot per minute mechanical pump with water trapping reservoir.
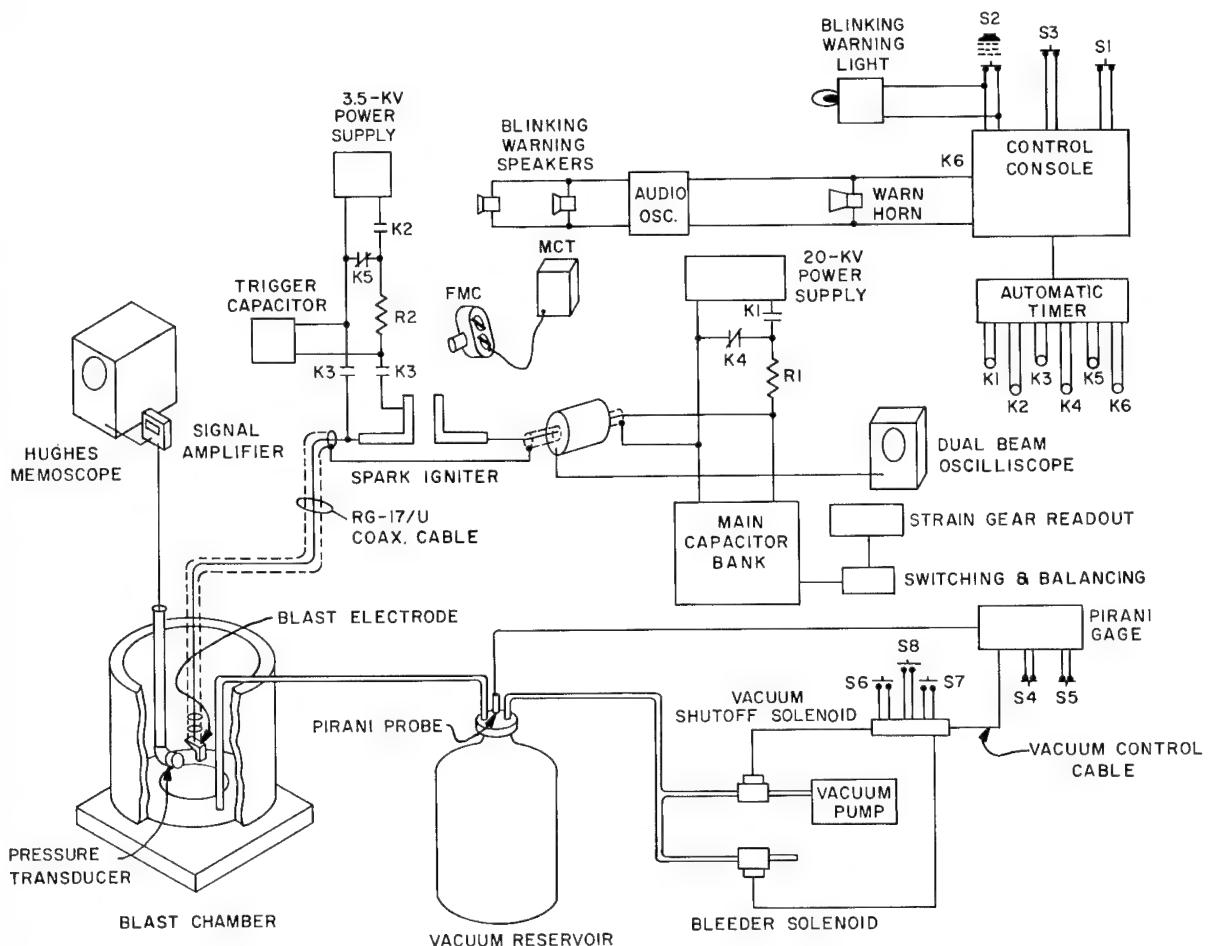
Figure 57.—Original configuration, electrical high energy forming system.

S1 Switch power on	S8 Switch remote vacuum pump start	K6 Relay—personnel warning
S2 Switch-combination-safety		R1 Current limiter—main bank
S3 Switch emergency stop	K1 Relay—main bank charge	R2 Current limiter—trigger
S4 Switch vacuum pump start	K2 Relay—trigger charge	
S5 Switch vacuum shutoff solenoid	K3 Relay—fire	FMC Movie camera, fastex, 8,000 fps
S6 Switch remote vacuum shutoff solenoid	K4 Relay—main bank safety discharge	MCT Timer, movie camera, operates from relay K6
S7 Switch vacuum bleeder solenoid	K5 Relay—trigger safety discharge	CT Current transformer

Charge current limiters: oil immersed resistors in plexiglas containers.

Discharge electrodes: brass construction with provisions for insertion of wire (fig. 58).

Figure 58.—View of early electrodes, wire, pressure transducer and adapter, transducer mounting pipe, and 5½-inch die.

Blast chamber: approximately 20 inches in diameter, 3 feet high with 1-inch-thick steel walls.

Control console: completely programmed, all events automatic after start button is pressed. "Dial combination locked" main switch, "panic button," vacuum gage readout and complete sequence lights included.

Instantaneous power level: 48 megawatts or 64,500 horsepower.

The present EHF system, called Medusa, has 240,000 joules capacity and is schematically shown in figure 59. Aside from the much larger capacitor bank, the main difference between the original and the present installation is in the transmission line and the switching system. After exhaustive switch testing at MSFC, ignitrons were selected. In all, the present EHF system at MSFC consists of the following:

Main Bank Capacitors: 80 Dubilier low-inductance, fast-discharge type, connected in a parallel plate construction, providing 1200 microfarads at 20 kilovolts, and mounted on racks from floor to ceiling. There are 10 separately controlled banks of 24,000 joules each, triggered independently by pulse delay generator.

Trigger capacitors: 4 microfarads each, charged to 8000 volts.

Switching system: 40 size A No. 7703 ignitrons connected in parallel.

Transmission line: 80 Rex brand No. V-1431 cables connected in parallel for lower inductance.

Main bank power supply: 2 amperes at 20 kilovolts.

Trigger power supply: Chicago condensor type, delivering 5 milliamperes at voltages up to 15 kilovolts.

*Vacuum system:* Kinney 8 cubic foot per minute mechanical pump with water trapping reservoir.

Charge current limiters: oil immersed resistors in plexiglas containers.

Discharge electrodes: brass construction. See forming head in figure 59.

Blast chamber: approximately 7 feet in diameter and 8 feet deep, steel construction and shock mounted in earth.

Instantaneous power level: 2400 megawatts or 3,220,000 horsepower.

Control console: completely programmed, all events automatic after start button is pressed. "Dial combination locked" main switch, "panic button," vacuum gage readout and complete sequence lights included. The complete control console is shown in figure 60.

Tooling requirements for EHF work are, in general, similar to those used in the chemical explosive forming. Only a female die of a desired contour is needed, with a draw or hold-down ring and a provision for vacuum drawing under the blank. When configuration of the part is suitable, a ring die without cavity can be used for free forming the part.

A die should have generous draw radius to avoid excessive thinout or stretch of the material. The hold-down draw ring must be capable of producing only sufficient pressure on the blank to prevent wrinkling, without restricting proper drawing of the material. For use in bulging tubular shapes, the die is usually split and held in position by means of a tapered cylindrical die
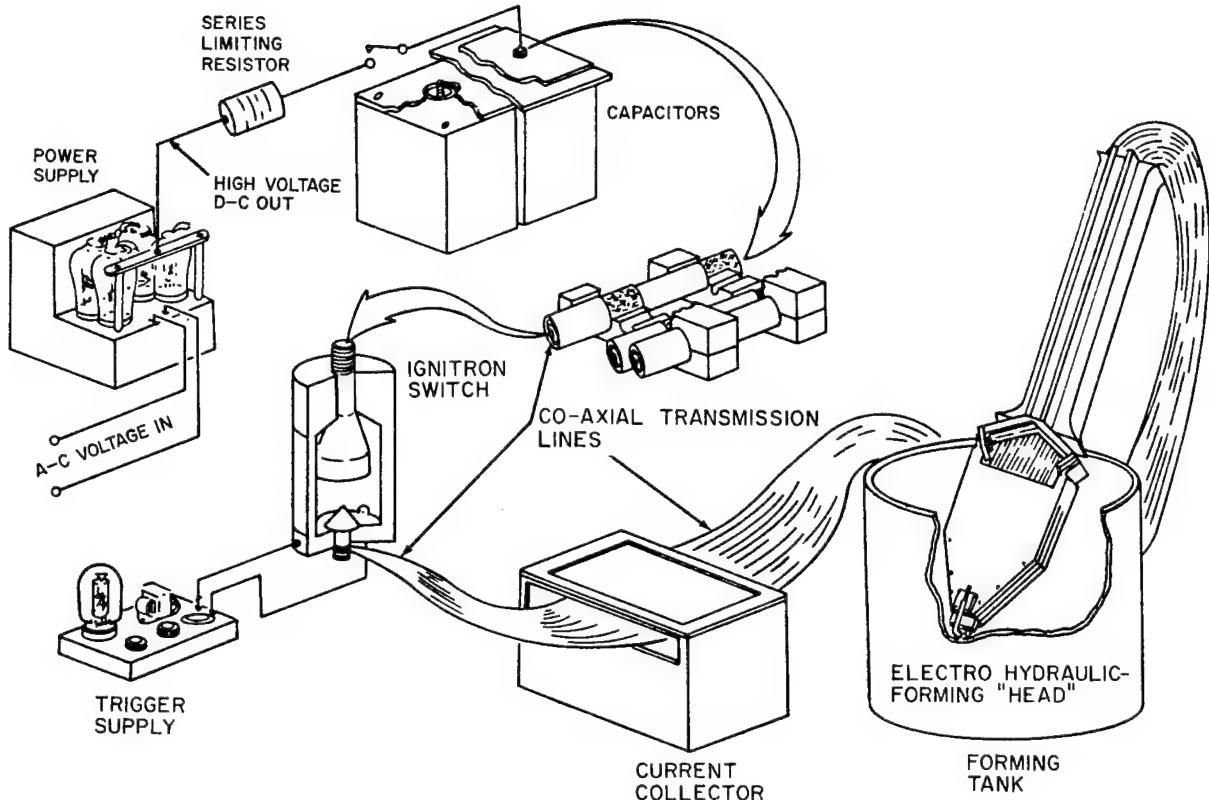
Figure 59.—Electrohydraulic-forming system.

Figure 60.—Control console for 240,000-joule capacitor bank.

holder. If very few parts, each requiring few discharges, are to be formed, a die can be made of fiberglass-reinforced epoxy plastic. However, the epoxy die surface has a tendency to craze and crack under repeated impact of the discharge and requires considerable maintenance. Cast Kirksite dies stand up quite well in EHF work and do not require maintenance.

As a part of tooling the electrodes are generally classified into three types: coaxial, axial or opposed, and parallel.

The original MSFC installation had a coaxial electrode arrangement, as shown in figures 57 and 58. The 5½-inch-diameter die with its draw ring, used during tests at MSFC, is also shown in figure 58. A parallel electrode arrangement with multiple transmission lines is shown in figure 59 in the forming tank. This configuration is used presently at MSFC. Figure 61 shows a variant of a parallel electrode arrangement used by an MSFC contractor for another sponsor to form

rather large parts, up to 68 inches in diameter. In this case, the electrodes are easily adjustable for spacing (gap between electrodes) and stand-off distance. The figure illustrates an arrangement in which the die is a part of the water tank, except that it is not "a closed chamber filled with water" idea used at MSFC, and mentioned previously in this article, as noncompressibility of water is not fully utilized.
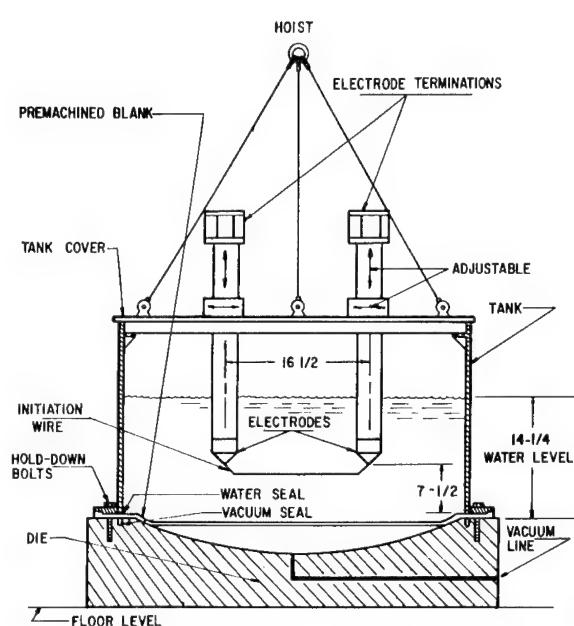

Figure 61.—Parallel electrodes and die for electrohydraulic forming of 40-inch closure heads.
(All dimensions in inches.)

Figure 62 illustrates an opposed or axial electrode configuration where spacing is easily adjustable, but where the standoff distance is fixed. This arrangement facilitates substantial production runs of relatively small parts.

Since the EHF efforts at MSFC have been largely basic in nature, no really large parts have been formed by this technique so far, but size limitations eventually are to be studied. Some of the parts experimentally formed in the original 24,000-joule installation are shown in figure 63. Figures 64 and 65 show typical parts electro-hydraulically formed using the present 240,000-joule installation. The first part is a ¼-inch-thick 302 stainless steel pressure vessel end made for the Centaur Program. The second part is a multicell space vehicle model bulkhead made of 0.063-inch 5052 aluminum alloy. In forming

this part, it was found to be advantageous to trim the blank asymmetrically with regard to the stretch and draw conditions, which are normally aggravated by the asymmetry. Appropriate trimming of the blank prior to forming finally made it possible to form this part.
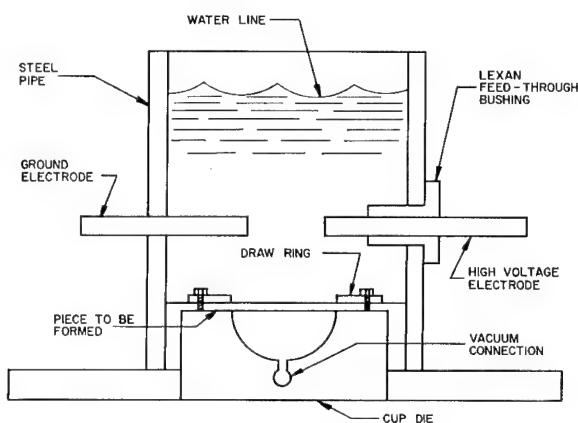

Figure 62.—Opposed electrodes.

Figure 63.—Typical hemispheres and other test parts largely of 5086-0 aluminum, 0.063-inch thick formed by electric discharge technique.
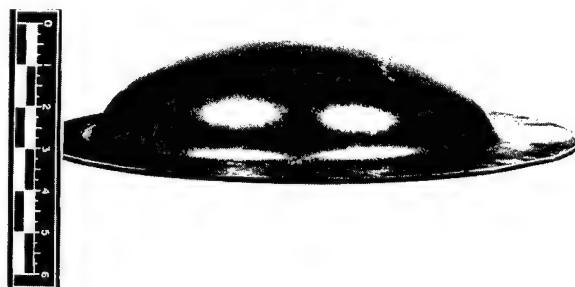
Figure 64.—One-quarter-inch thick stainless steel pressure vessel end.
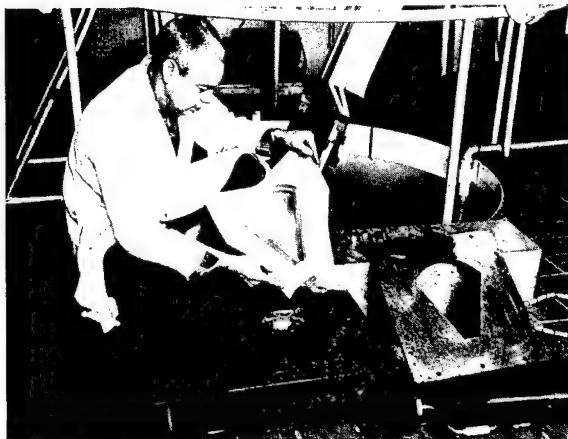
Figure 65.—Electrohydraulic-formed part from asymmetrically trimmed blank.

One of the facts brought out during EHF work at MSFC was that repeated use of the same water for several shots results in lowered forming efficiency. It appears that the reduced efficiency is because of some shunting of current through the fluid, outside the desired path, through the exploding bridgewire plasma column. It follows, then, that water in the tank should be replaced after a few shots, the allowable number of shots being proportional to the size of the tank or blast chamber.

Another MSFC-sponsored contractor performed an extensive series of tests, forming 10-inch-diameter hemispheres in two aluminum alloys and in one stainless steel alloy, all 0.090 inch thick and all in annealed condition, by five different methods, including electrohydraulic. The objective of the tests was to compare the results of forming these alloys by high energy rate and conventional processes, with emphasis on the influence of strain rate on various properties.

The EHF equipment used for tests at the contractor's plant is a capacitor bank, consisting of 64 capacitors arranged in four groups of 16 capacitors each for a total capacitance of 960 microfarads ($15 \times 64 = 960$). When charged to a maximum of 18 kilovolts, the capacitor bank can deliver 155,000 joules of energy to an external load. An appropriate charging power supply, switching apparatus, and flexible coaxial interconnection cables are also parts of the installation. The forming tank, a closed type with hinged door and axial electrodes, is shown in figure 66. This illustration indicates the use of a 10-inch-diameter open ring die for free forming, while figure 67

shows a closed female die, which also can be mounted in the hinged door of the tank. Both dies were used at various stages of the test series. With charging voltages up to 12 kilovolts, forming pressures obtained were up to 37,600 pounds per square inch and were directly proportional to the
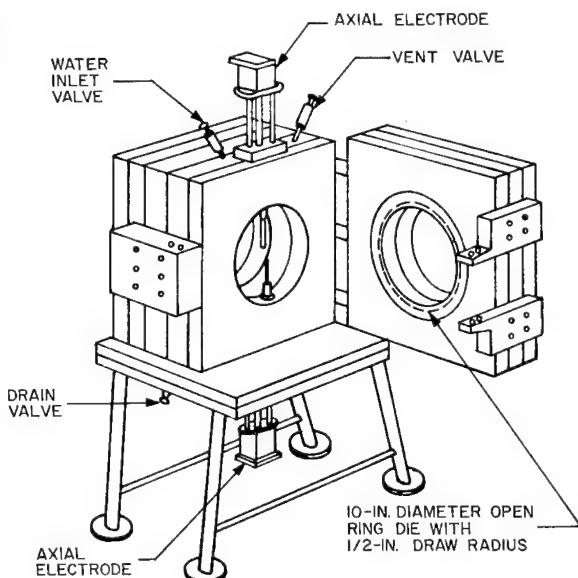

Figure 66.—Closed tank used for electrohydraulic experiments.
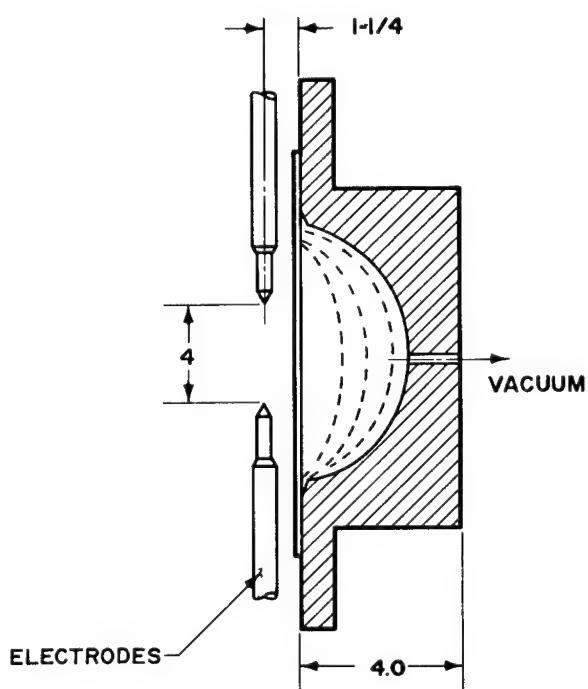
Figure 67.—Closed female die.
(All dimensions in inches.)

discharge energy. The calculated efficiencies were on the order of 15 percent for aluminum alloy and 10 percent for stainless steel hemispheres.

To determine strain rates in free forming 2219-0 aluminum alloy domes, a ½-inch by ½-inch square was painted on the center of the blanks before their installation into the 10-inch-diameter ring die. High-speed motion pictures taken during the forming operation recorded the increase in the size of the square and provided a time/dimension relationship which was used to calculate rate of strain. Measurements of the size of actual image on film were made on an optical comparator.

It has been reported that, in general, for electro-hydraulic forming of the domes, the maximum strain rates ranged from 130 to 500 inches per inch per second. Based on the results of a large number of tests, it can be said that no significant difference in mechanical properties from specimens formed in this range of strain rates was discerned. The ultimate strength, the yield strength and the percent elongation responded similarly with strain for all strain rates in dome forming of 2014-0 aluminum alloy and 321 stainless alloy. It was also observed during the tests that, at equal strain (as indicated by thinout of dome center), lubricated blanks produce deeper domes since drawin of metal from flange is increased. Consequently, lubrication reduces the strain rate since the dome shape is obtained with less stretch of the metal.

Another contractor developed a promising technique that takes advantage of the fact that removal of the oxide surface from the blank greatly extends the forming range of the material. The oxide coatings cause high dislocation densities which provide considerable resistance to forming. The contractor has successfully sealed materials in a layer of paraffin (after the oxide has been removed). These materials then exhibited about 100 percent increase in elongation over uncoated control specimens when 2014-T6 aluminum alloy was used.

MAGNETIC FORMING

Although original achievement of intense magnetic fields goes back about 40 years, the practical possibilities of metal forming by these fields first became known only about 9 years ago. The magnetic metal high-energy-rate forming (HERF)

technique, sometimes called electromagnetic forming or magnetic pulse forming, utilizes the ultra-rapid capacitor discharge into a suitably arranged electric coil to produce necessary forming forces.

Very high momentary currents passing through the coil set up an intense transient magnetic field around it. The rapidly rising field induces large eddy currents in an electrically conducting work piece in proximity, and these currents, in turn, set up an intense magnetic counter field. This is schematically illustrated in figure 68. The "magnetic pressure" thus created (which varies directly as the square of the field strength) then accelerates the metal away from, or toward, the coil, depending on how the discharge into the coil is programmed.
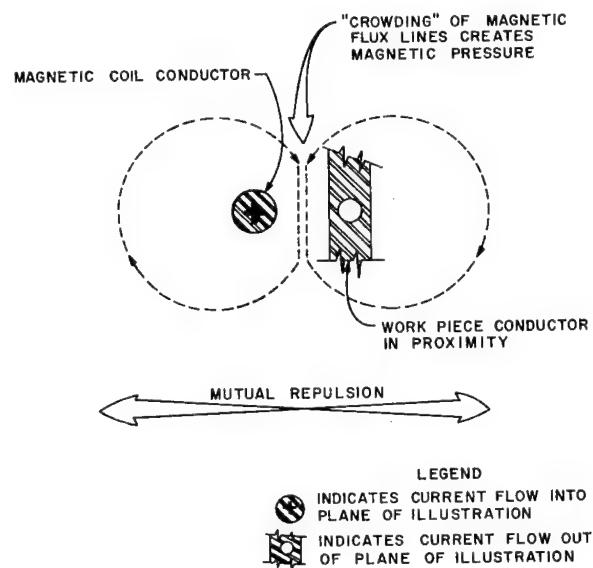
Figure 68.—Coil magnetic field interaction with induced conductor magnetic field in proximity.

To create attraction rather than repulsion forces between work piece and coil, a magnetic field is built up relatively slowly, and is allowed to propagate well through the conductor. Then, by causing a rapid current decay in the coil, the magnetic field trapped in the space beyond the conductor must collapse, and, in so doing, generates forces tending to drive the conductor into, rather than away from, the coil.

Since high-density fields exert equal and opposite forces on work piece and coil, the coil must be structurally and inertially rigid enough to accomplish forming of the metal without disintegrat-

ing. Sometimes, however, it may be desired to utilize a "one-shot" expendable coil. An idealized coil is illustrated in figure 69. It is an obvious feature of the process that there will be no forming forces set up in a conductive work piece unless it is in the intense magnetic field of the coil.

$$\text{STORED ENERGY} \quad \tfrac{1}{2}\,cv^2 \longrightarrow \tfrac{1}{2}\,LI^2 \longrightarrow \tfrac{1}{8\pi}\int H^2\,dv$$
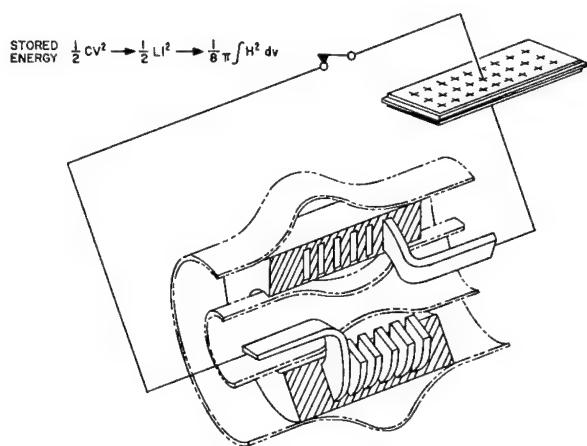
Figure 69.—Idealized magnetic forming, bulging or constriction coil.

Another feature is that the magnetic field adapts itself to the shape of the work piece and, since there is no physical contact between the tool (coil) and the work piece, there are no areas of pronounced localized pressure as in forming with rigid tools.

It is in the area of tooling that the magnetic-forming technique has basic cost advantage over other HERF techniques, since in many cases only a relatively inexpensive coil is required for forming rather than rigid tools. Magnetic forming coils are generally of air core construction because ferromagnetic materials reach the magnetic field saturation point at much lower flux densities than those required for many other applications. Field-shaping inserts, or field concentrators, are sometimes used. These are of a specifically shaped auxiliary material, solidly positioned so as to concentrate or modify the field in the desired direction.

Modern HERF methods, using capacitor discharge into a suitable coil, can easily produce a transient magnetic field strength of 300,000 gauss, resulting in instantaneous pressure forces of approximately 50,000 pounds per square inch for a few microseconds, allowing application of this technique to numerous metal-working operations. With appropriate coil design, this technique can be used for dieless swaging, forming, assembling, bulging, piercing, fastening, coining or embossing, and blanking electrically conductive metals. There are probably other applications not yet developed.

Many applications utilize much lower energy levels than the one just mentioned. For example, convolutes are formed quite regularly in thin-walled cylinders with only about 15 kilogauss.

In blanking or punching, there is another advantage for economy in tooling. A simple wooden or bakelite die with a hole in it is placed beneath a piece of sheet metal into which a hole is to be punched. The magnet coil is then placed on top of the sheet metal. When the coil is pulsed, the circular sector of metal is driven through the hole in the wooden die with such high impulse that the wooden die itself is left perfectly intact. It appears, then, that wooden or bakelite dies are adequate for certain limited blanking operations.

Nonconductive or low-conductivity materials may require special techniques such as a high conductivity auxiliary coating or wrapper around the work piece to develop the necessary force. About 5 to 10 times more field strength is required to form common irons and steels than to form aluminum or copper. For some stainless steels, the ratio can be as much as 50 or 60 to 1.

Another item of considerable importance in magnetic forming is the frequency at which the magnetic field oscillates or is pulsed, since the depth of penetration of the field is dependent on frequency, as well as on the resistivity and permeability of the material. This is particularly important in swaging or fastening operations, since too deep penetration of the field causes the driven material literally to "back-up" from the material to which the fastening is desired.

The equipment needed to produce high-intensity transient magnetic fields by means of the rapid discharge of capacitor-stored electrical energy is very similar to the arrangement used in electrohydraulic forming. The difference is that the discharge is directed into a forming coil instead of into a forming head with a bridgewire. In fact, the same system can be used for either if it is properly designed, except that the loads are different since forming coils are always more inductive than the plasma loads of electrohydraulic

forming.   In addition, energy discharges tend to be more oscillatory.

The simplified schematic diagram of a magnetic-forming system is shown in figure 70.   As indicated in the equation in figure 69, the stored energy in capacitors is in the form of an electric field, proportional to the capacitance and to voltage squared.   By means of suitable switching apparatus, the electric field energy is quickly converted into magnetic field energy in the forming coil where the magnetic field energy now is proportional to coil inductance and to the square of the coil current.

Typical voltages run from about 4000 volts to 20,000 to 30,000 volts, while currents range from thousands to hundreds of thousands of amperes. Discharge times range from a few microseconds to several hundred microseconds.   Circuit resistive losses usually are negligible.

Both electrohydraulic forming and magnetic forming have been accomplished on the 240,000-joule capacitor bank installation in the MSFC Manufacturing Engineering Laboratory.

Numerous magnetic forming developments have been accomplished at MSFC.   Magnetic forming of stiffening convolutes in thin-walled aluminum alloy cylinders originated because of an Advanced Saturn V vehicle requirement, which at the time involved the development of stiffening members in a 50-foot-long seamless tube about 25 inches in diameter.   The tube, with magnetically formed stiffening convolutes, and the coil, with 100-foot long transmission line, are shown in figure 71. The field strength requirement for this operation is rather low.   Only 10 to 30 kilogauss are needed, depending on wall thickness and strength of the material.
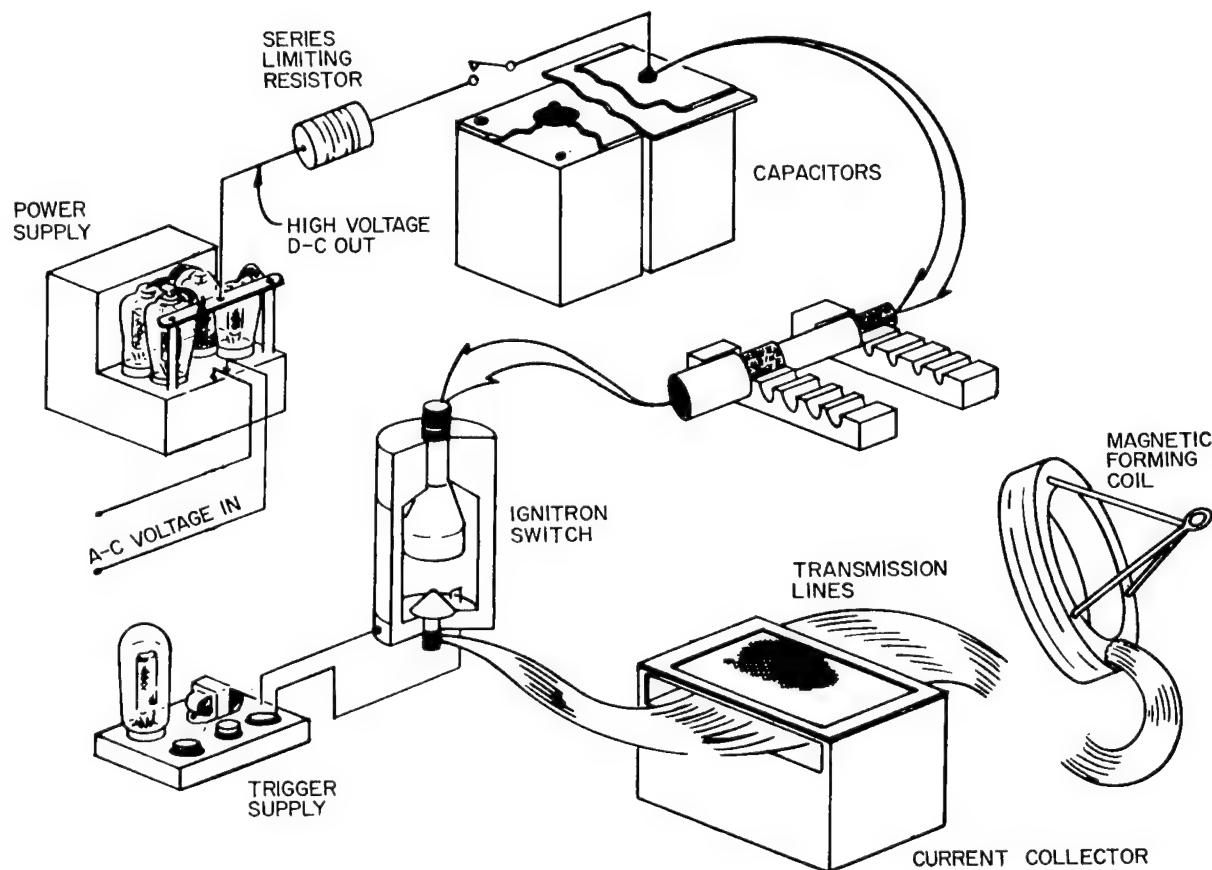

Figure 70.—Electric discharge forming system.

Figure 72 shows a 4-foot diameter aluminum alloy cylinder with the forming coil suspended above. The difference in convolute contours is a result of deliberately varied energy level discharges and inertial effects. It is seen then, that constant or variable contour convolutes can be made in long metal tubes of relatively large diameter without using dies where such requirements may exist in industrial operations.
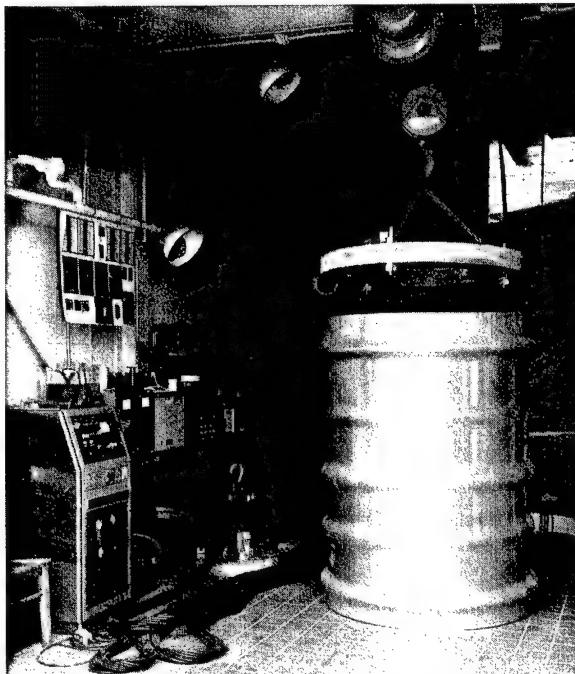

Figure 72.—Different convolutes in test cylinder, 4-foot diameter coil.

Another application of the intense transient magnetic field principle is currently under development at MSFC. A magnetic fastening system called Magnelok is ultimately oriented toward providing an entire tooling system consisting of power supply, switches, transmission lines, and tools for possible future use in space. Similar equipment is also being developed for direct application in space vehicle fabrication and assembly.

Basic operation of the Magnelok involves swaging a threadless sleeve onto a bolt of a simple design. The magnetic field constricts the sleeve on the bolt, causing instantaneous fastening, and, at the same time, pulls the parts tightly together. Figure 73 schematically illustrates the principle on which Magnelok tool swaging action is based,

Figure 71.—Magnetically formed convolutes in 25-inch diameter aluminum alloy thin-walled cylinder.

while figure 74 shows typical Magnelok hardware. In the right lower view of figure 74 it can be seen that the sleeves are swaged with such force that the threads are formed inside sleeves, and indentations are made longitudinally into the previously machined grooves of the bolts.
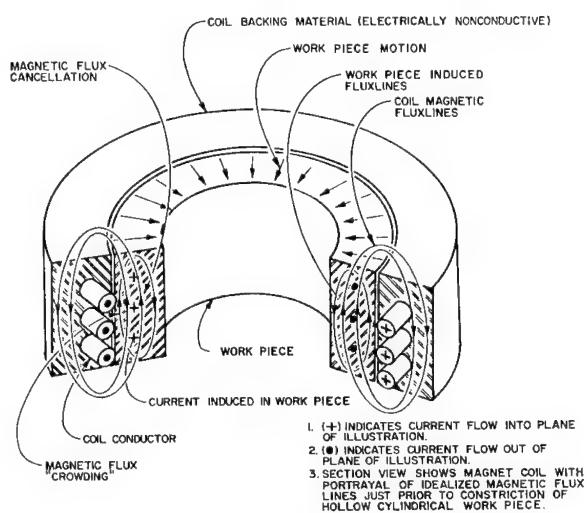

Figure 73.—Magnet coil and work piece.

It is thought that the power, speed, and simplicity of the Magnelok operation could benefit not only the aerospace industry, but the auto industry as well in the general area of fasteners. Evaluation of Magnelok fasteners, with respect to equivalent aircraft fasteners, is in progress.

A MSFC contractor ran extensive series of tests forming 10-inch diameter hemispheres. Five different methods of forming were employed including electrohydraulic and magnetic forming. The objective of all the tests was to compare the results of forming these alloys, both by high energy rate and by conventional process, with emphasis on the influence of strain rate on various properties of the materials involved. Strain rates were determined by use of high speed motion pictures taken during forming operations.

The magnetic-forming technique was included to obtain higher values of strain rate at the same discharge energies used for the electrohydraulic strain rate tests.

The contractor's 155,000-joule capacitor bank discharge was directed into a contractor-fabricated 9-inch-diameter coil of 139 microhenries induc-

Figure 74.—Typical Magnelok hardware.

tance. Construction of this coil is shown in figure 75. The arrangement for free-forming the hemispheres, including installation of the coil and position of the work piece, is illustrated in figure 76.

Table II gives typical data on energy input and results obtained, including peak coil current and the strain rates.

It will be noted that maximum strain rates re-
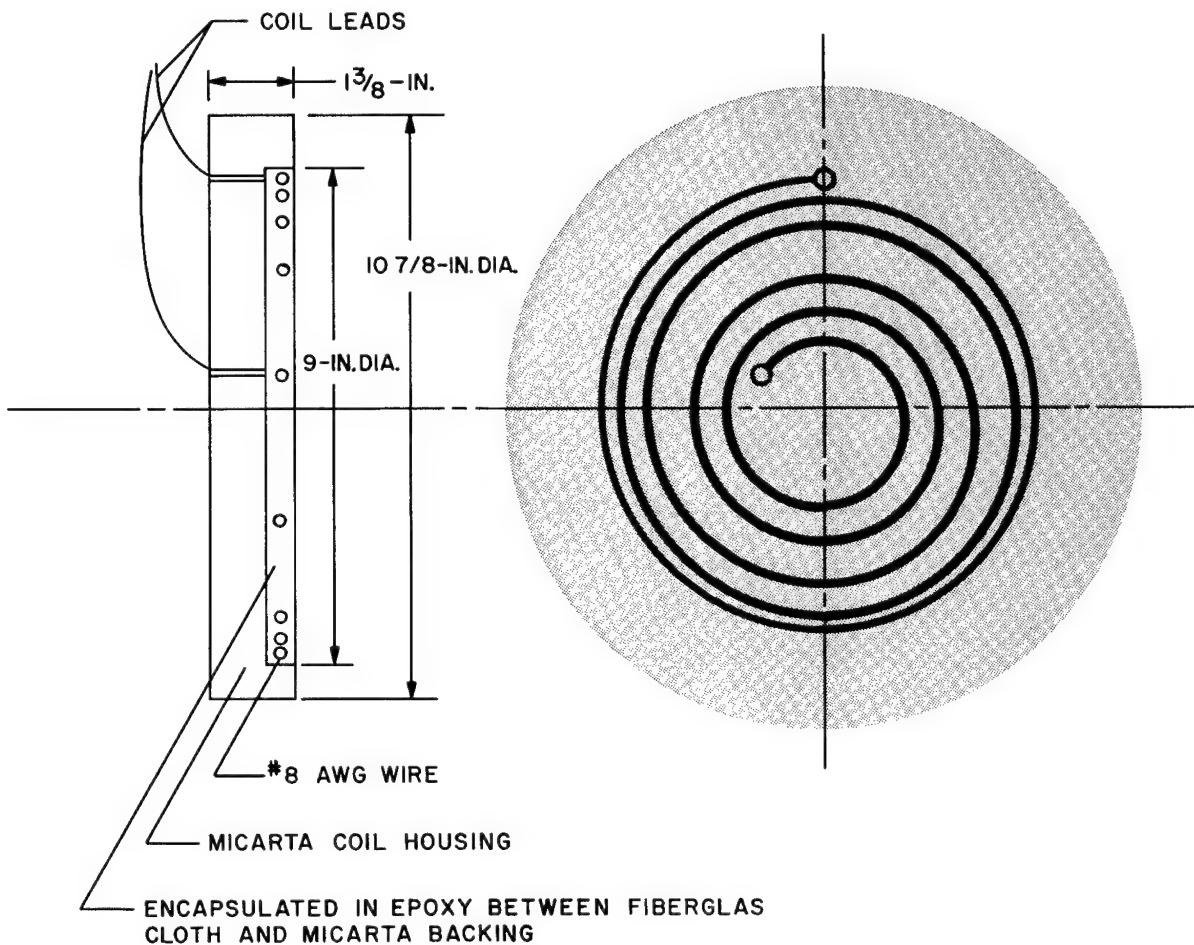
Figure 75.—Construction of six-turn spirally wound coil of 139 microhenries.
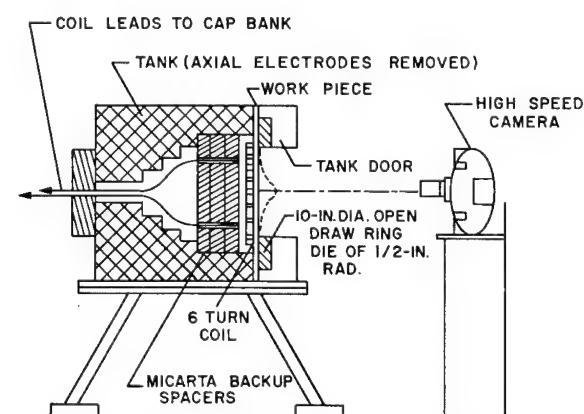
Figure 76.—Method used to house six-turn coil in closed tank for strain-rate measurements.

ported are all higher than 500 inches per inch per second obtained in electrohydraulic forming. The highest rate shown was 877 inches per inch per second. However, this and other high rates apparently did not have any significant influence on the mechanical properties of the two aluminum alloys tested. The stainless steel alloy hemispheres were not formed magnetically, since higher yield strength and lower conductivity of this alloy would produce less deformation, and therefore, less strain per discharge.

In conclusion, it can be stated that, although magnetic forming and other applications of intense magnetic field are very recent, a great deal more can be anticipated in the future along the lines of

Table II.—Typical data obtained with strain-rate measurement equipment (fig. 76).

Input energy		Volume cc	Specimen No.	Alloy	Shot No.	Average strain,	Max. strain,	Dome depth	Peak coil current,
kv	joules					in./in./sec	in./in./sec	in.	amp
8	30,720	1,590	M2	2219-0	1	200-300	700-800	3.065	21,000
8	30,720	1,580	M3	2219-0	1	247.3	723.0	3.145	21,000
4.5	9,720	900	M1	2219-0	1	97.7	675.0	1.445	11,700
8	30,720	1,740	M2	2014-0	1	253.5	877.0	3.365	21,000
7.5	25,900	1,660	M3	2014-0	1	100-200	700-800	3.14	19,300
5	12,000	1,100	M1	2014-0	1	142.8	769.0	1.825	13,100

Common forming conditions:

0.092-inch thick flat blank of 17½-inch diameter.
10-inch diameter. Open draw ring die of ½-inch draw radius.
6-turn spirally wound flat coil of 139 microhenries.
Inductance housed in closed die.
960-microfarad capacitor bank.

new utilization and new developments of the same basic principles. In fact, there already is a commercially available magnetic-forming machine of 12,000 joules capacity.

ROLL EXTRUSION TECHNIQUE

In the Advanced Saturn V, S-1C Stage construction, there are requirements for thin-walled stainless steel tubes or ducts (five per vehicle) approximately 40 feet long and 20 inches inside diameter. These ducts, called suction lines, carry liquid oxygen (LOX) from the LOX tank (located above the fuel tank) through the fuel tank to the engines, which are attached to the thrust structure below the fuel tank.

As an integral part of the fuel tank, there is an equal number of aluminum alloy thin-walled tunnels, 25 inches inside diameter, through which the LOX suction lines pass. The arrangement of tunnels and suction lines is shown in figure 77, where the tunnels and suction lines are indexed 9 and 10, respectively. The size of the S-1C booster and its components is quickly appreciated by comparing it with the man in the picture. The illustration was drawn to scale.

While seamless one-piece construction was desired for the LOX tunnels from the beginning, the original fabrication utilized sectionalized, rolled, and welded sheet metal material. However, the new roll extrusion technique allows both the LOX suction lines and the tunnels to be fabricated as continuous one-piece seamless tubes.

Roll extrusion is a metal forming technique in which a driven hollow metal billet is roll extruded over a rotating cylindrical mandrel under a pressure of three rolls to a desired outside diameter, wall thickness, and length. Although roll extrusion, in this case, does not involve forming of sheet or plate material, it was decided to include the technique in this report since this method is new and unique.

A contractor, now sponsored by MSFC, had many years of experience in procuring and working with aircraft quality step-tapered steel spar tubes for helicopter blades. Two years ago, this contractor developed his own facility and the capability to achieve quality and dimensional accuracy on relatively large diameter seamless tubes not attainable before anywhere.

Roll extrusion, referred to by the contractor as "Par-Form," is done on a "Floturn" machine, shown in figure 78 in overall view. The machine utilizes three cam-positioned pressure rolls to work a precision-machined billet against a hardened and ground steel mandrel. As the billet diameter is being reduced, the metal is forced out or roll extruded along the mandrel of proper diameter and length. Roll holders are provided to support the work piece as it flows off the end of the mandrel to its full length.

Mandrels and pressure rolls are turned, then hardened and ground. Only two-dimension cams are required to control wall thickness of the tube or taper locations (if any). No special form dies are required. Rotation of the cam templates is controlled by a gear train from the carriage lead
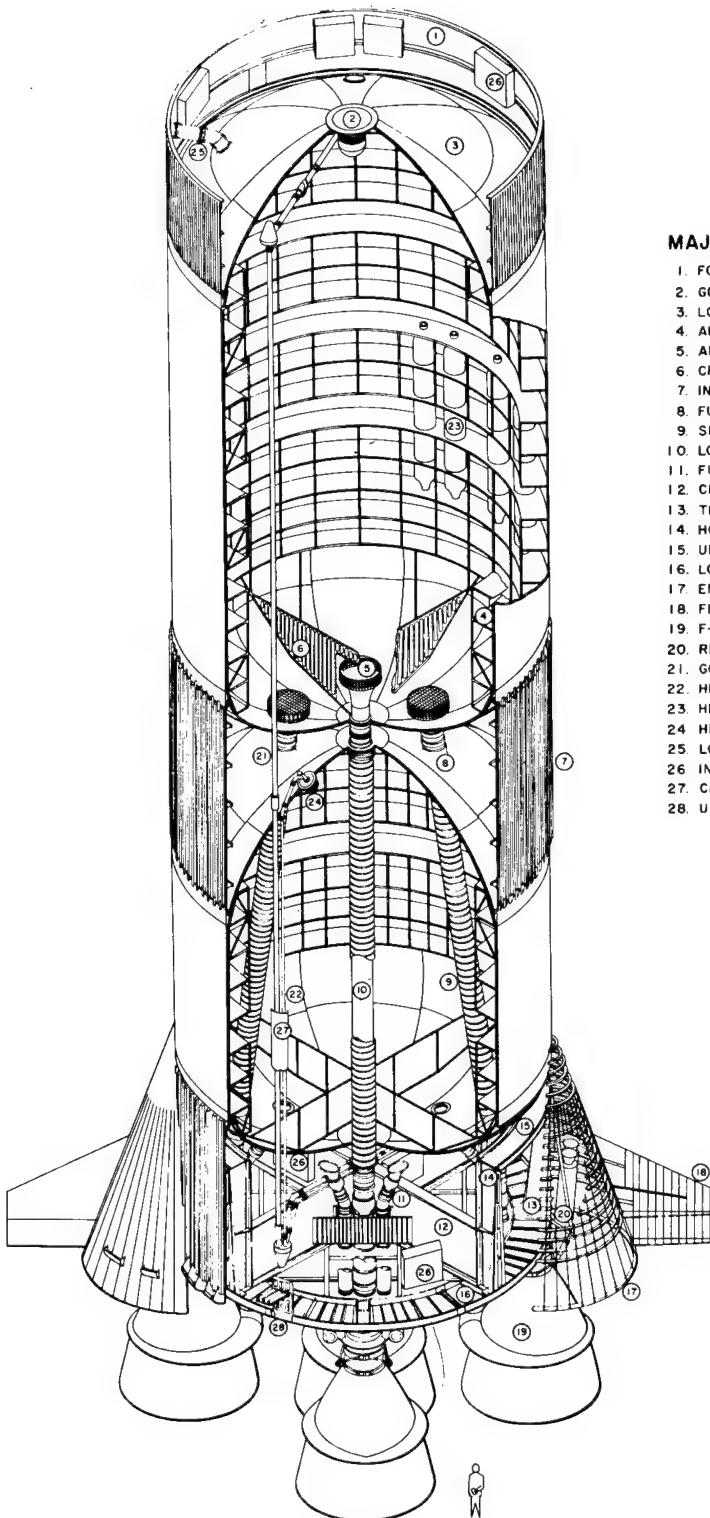
MAJOR COMPONENTS

1. FORWARD SKIRT STRUCTURE
2. GOX DISTRIBUTOR
3. LOX TANK
4. ANTI-SLOSH BAFFLES
5. ANTI-VORTEX DEVICE
6. CRUCIFORM BAFFLE
7. INTERTANK STRUCTURE
8. FUEL TANK
9. SUCTION LINE TUNNELS
10. LOX SUCTION LINES
11. FUEL SUCTION LINES
12. CENTER ENGINE SUPPORT
13. THRUST COLUMN
14. HOLD DOWN POST
15. UPPER THRUST RING
16. LOWER THRUST RING
17. ENGINE FAIRING
18. FIN
19. F-1 ENGINE
20. RETRO ROCKETS
21. GOX LINE
22. HELIUM LINE
23. HELIUM BOTTLES
24. HELIUM DISTRIBUTOR
25. LOX VENT LINE
26. INSTRUMENTATION PANELS
27. CABLE TUNNEL
28. UMBILICAL PANEL

Figure 77.—Saturn V, S-1C Stage, general arrangement.
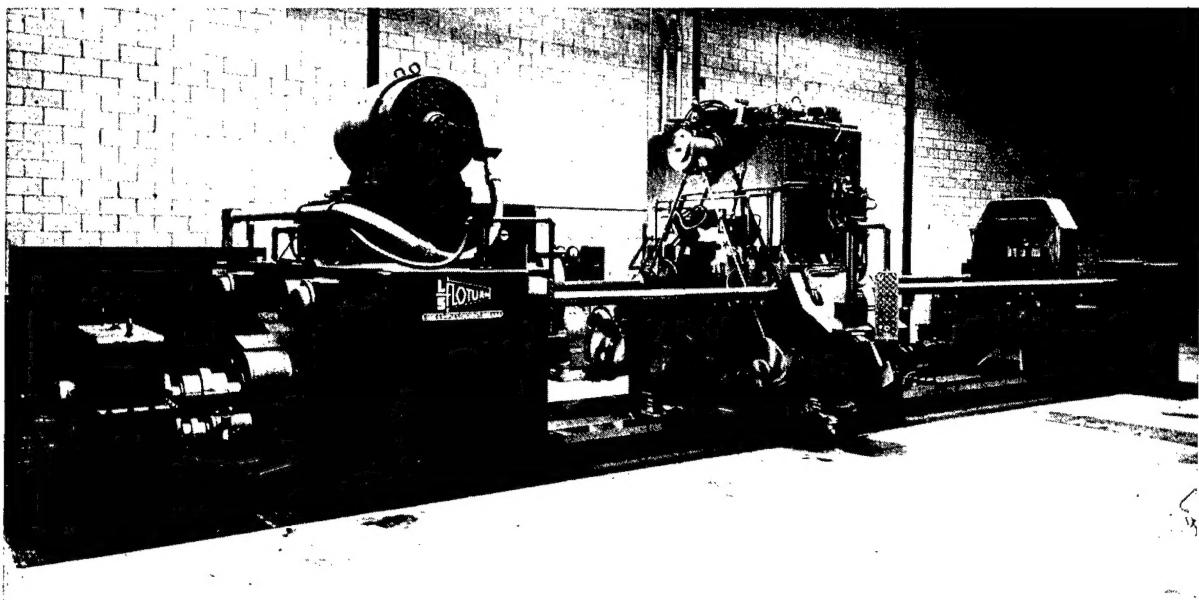
Figure 78.—"Floturn" machine for roll extruding LOX ducts and tunnels.

screws to assure maximum uniformity of section thickness. The carriage, with its templates and hydraulically actuated working rollers, may be programmed to operate in either direction, as dictated by the design of the part. Reduction of the billet diameter by pressure rolls is done cold, although the mandrel and billet may be heated when circumstances dictate.

The machine can handle seamless tubes of 3 inches to 26.5 inches outside diameter, wall thickness of 0.015 inches to 1.5 inches with an accuracy of 0.002 inches, and surface finish of 15 root mean square on inside diameter and 30 root mean square on outside diameter.

Par-forming of the seamless stainless steel LOX suction line starts with a 321 stainless steel hollow-forged billet, purchased in accordance with the contractor's drawing. After thorough inspection and identification, the billet is bored on a lathe to $19.995 \,{}^{+0.005}_{-0.000}$ inches (16 root mean square) inside diameter, then turned to appropriate outside diameter (63 root mean square). The Par-Form blank is then placed on the 20-foot-long mandrel in the Floturn machine. After several passes, intermediate anneal, and continual in-process inspection, the seamless tube has 20.000 ± 0.015 inches inside diameter with $0.080 \,{}^{+0.010}_{-0.000}$ inch wall thickness, and is approximately 38 feet long. One of the inspection steps includes a pressure test to 280 pounds per square inch gage.

The tube is cleaned, final inspected, wrapped in kraft paper, and prepared for shipment in a special container to another contractor for further fabrication into a complete LOX suction line duct. Actual Par-Form operation on the Floturn machine is shown in figure 79. Figure 80 illustrates wall thickness inspection in process with vidigage.

The 2219-0 aluminum alloy tunnels are processed and Par-Formed in a manner similar to that used for the stainless steel LOX suction lines. However, the billet is machined to $24.995 \,{}^{+0.005}_{-0.000}$ inches on the inside diameter and 27.000 ± 0.005 inches on the outside diameter. The surface smoothness is 16 root mean square on the inside and 63 root mean square on the outside. The mandrel has a 24.985-inch diameter and is approximately 30 feet long.

During numerous passes of Par-Forming, the technique involves not only cleaning and continual inspection, but also stress relief and solution heat treatment of the tube. After forming is completed, the seamless aluminum alloy tube has an outside diameter of 25.190 ± 0.015 inches, a wall thickness of 0.095 ± 0.003 inch, and a length of approximately 44 feet. A 55-inch-long section on one end has a wall thickness of 0.224 inch because of special welding requirements. The tube is then inspected, cleaned, and age hardened to —T62 condition. Later, circular reinforcements are bonded on the outside surface of the
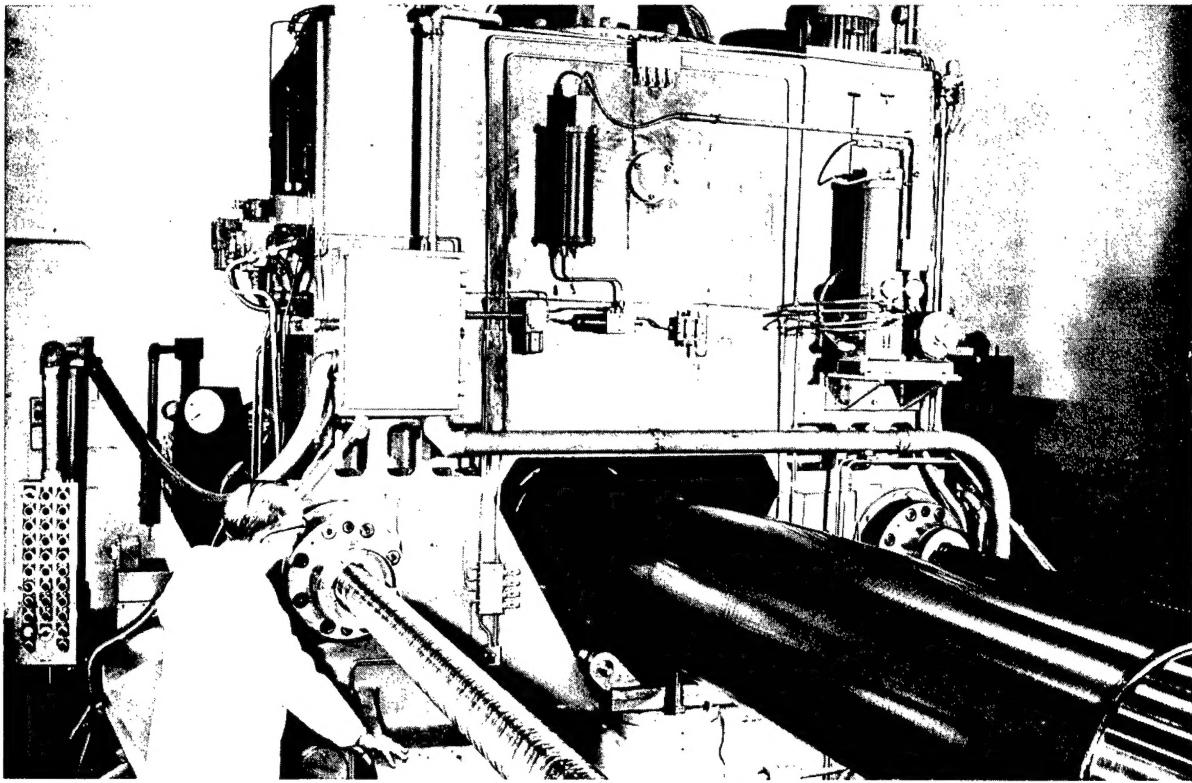
Figure 79.—Roll extruding of seamless tube on "Floturn" machine.
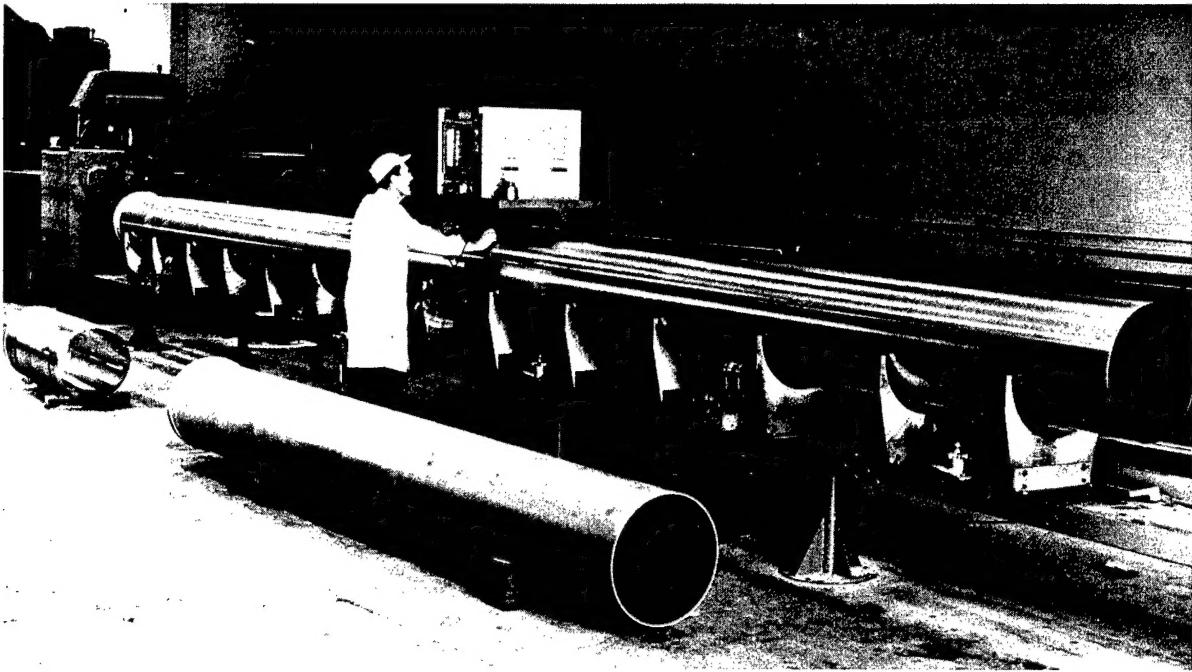
Figure 80.—Wall-thickness check with Vidigage.

tube and the assembly is anodized for protection against corrosion. The tube is final inspected and packaged in the same special container for shipment to MSFC or to the prime contractor.

BIBLIOGRAPHY

1. Alcoa Green Letter: Aluminum Alloy 2219. Dec. 1962.

2. Boeing Company: Historical Summary of Bulge Forming Gore Parts. MRIR, No. 4-026.

3. Boeing Company: Preliminary Process Outline, LOX Tunnel.

4. Carson, Robert W.: High-Energy-Rate Forming. Product Engineering, Oct. 15, 1962.

5. Christiana, J. J.: Electrohydraulic Tooling for Dome Forming. Republic Aviation Corp., SP63-184. ASTME Technical Paper.

6. D'Aguanno, P.; and Pfanner, G.: Theoretical and Experimental Evaluation of High Energy Forming of Hemispherical Shapes in Metals. Republic Aviation Corp., Dec. 1963.

7. Erbin, E. F.: Titanium for the Mach 3 Transport. Titanium Metals Corporation of America.

8. Gauntt, Wayne M.; and Derbyshire, J.: Space Vehicle Corrosion. Ordnance Magazine, May-June 1964.

9. Glasrock Products, Inc.: Literature of.

10. Hot Forming Titanium Sheet. American Machinist/Metalworking Manufacturing, Jan. 8, 1962.

11. Inman, Nelson: Electrohydraulic Metal Forming Equipment. Republic Aviation Corp., SP63-185. ASTME Technical Paper.

12. Judge, John F.: Glasrock Applications. Missiles and Rockets, April 10, 1961.

13. Layton, R. E.; and Walls, W. O.: Let's Talk about Age Forming. Boeing Co.

14. Odor, Louis: Three Explosive Application to Metal Forming. North American Aviation, Inc., 849B. SAE Paper.

15. Pfanner, Gunther: Electrohydraulic Production Applications in Dome Forming. Republic Aviation Corp. SP63-186. ASTME Technical Paper.

16. Rinehart, John S.; and Pearson, John: Explosive Working of Metals. Macmillan Co., 1963.

17. SAE Production Forum Reports, 1952-1957.

18. Schwinghamer, R. J.: Electrical and Diagnostic Aspects of Electrohydraulic and Magnetic Forming. MSFC. 672C. SAE Paper.

19. Schwinghamer, R. J.: Electrohydraulic Forming. Machinery, Sept. 1963.

20. The Parson Corporation: Par-Form Components. Oct. 1962.

21. The Parsons Corporation: P-705-1035 Development of LOX Tunnel. Mar. 1963.

22. Wesley, R. H.: Principles of Electrospark Forming. Electro-Hydraulic Corp., 634C. SAE Paper.

23. Wilson, William S.; and Schwinghamer, R. J.: Magnetic Forming. MSFC. Industrial Research, Feb. 1963.

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